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Japanese Technology Evaluation Center



JTEC

JTEC Panel Report on

Display Technologies In Japan

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JAPANESE TECHNOLOGY EVALUATION CENTER

- SPONSOR** The Japanese Technology Evaluation Center (JTEC) is operated for the Federal Government to provide assessments of Japanese research and development (R&D) in selected technologies. The National Science Foundation (NSF) is the lead support agency. Paul Herer, Senior Advisor for Planning and Technology Evaluation, is NSF Program Director for the project. Other sponsors of JTEC include the National Aeronautics and Space Administration (NASA), the Department of Commerce (DOC), the Department of Energy (DOE), the Office of Naval Research (ONR), the Defense Advanced Research Projects Agency (DARPA), and the U.S. Air Force.
- PURPOSE** JTEC assessments contribute to more balanced technology transfer between Japan and the United States. The Japanese excel at acquisition and perfection of foreign technologies, whereas the U.S. has relatively little experience with this process. As the Japanese become leaders in research in targeted technologies, it is essential that the United States have access to the results. JTEC provides the important first step in this process by alerting U.S. researchers to Japanese accomplishments. JTEC findings can also be helpful in formulating governmental research and trade policies.
- APPROACH** The assessments are performed by panels of about six U.S. technical experts. Panel members are leading authorities in the field, technically active, and knowledgeable about both Japanese and U.S. research programs. Each panelist spends about one month of effort reviewing literature and writing his/her chapter of the report on a part-time basis over a twelve-month period. All recent panels have conducted extensive tours of Japanese laboratories. To provide a balanced perspective, panelists are selected from industry, academia, and government.
- ASSESSMENTS** The focus of the assessments is on the status and long-term direction of Japanese R&D efforts relative to those of the United States. Other important aspects include the evolution of the technology and the identification of key researchers, R&D organizations, and funding sources.
- REPORTS** The panel findings are presented to workshops where invited participants critique the preliminary results. Final reports are distributed by the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161 (703-487-4650). Panelists also present their findings in conference papers, journals, and books. All results are unclassified and public.
- STAFF** The Loyola College JTEC staff helps select topics to be assessed, recruits experts as panelists, organizes and coordinates panel activities, provides literature support, organizes tours of Japanese labs, assists in the preparation of workshop presentations and in the preparation of reports, and provides general administrative support. Mr. Cecil Uyehara of Uyehara International Associates provided literature support and advance work for this panel.

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FINAL REPORT

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FOREWORD

This report is one in a series of reports prepared through the Japanese Technology Evaluation Center (JTEC), sponsored by the National Science Foundation (NSF) and administered by Loyola College in Maryland. The report describes research and development efforts in Japan in the area of display technologies.

Over the past decade, the United States' competitive position in world markets for high-technology products appears to have eroded substantially. As U.S. technological leadership is challenged, many government and private organizations seek to set policies that will help maintain U.S. competitive strengths. To do this effectively requires an understanding of the relative position of the United States and its competitors. Indeed, whether our goal is competition or cooperation, we must improve our access to the scientific and technical information in other countries.

Although many U.S. organizations support substantial data gathering and analysis directed at other nations, the government and privately sponsored studies that are in the public domain tend to be "input" studies. That is, they measure expenditures, personnel data, and facilities but do not assess the quality or quantity of the outputs obtained. Studies of the outputs of the research and development process are more difficult to perform since they require a subjective analysis by individuals who are experts in the relevant technical fields.

The National Science Foundation staff includes professionals with expertise in a wide range of technologies. These individuals have the technical expertise to assemble panels of experts who can perform competent, unbiased, scientific and technical reviews of research and development activities. Further, a principal activity of the Foundation is the review and selection for funding of research proposals. Thus the Foundation has both experience and credibility in this process. The JTEC activity builds on this capability.

Specific technologies, such as displays, telecommunications, or biotechnology, are selected for study by individuals in government agencies that are able to contribute to the funding of the study. A typical assessment is sponsored by two or more agencies. In cooperation with the sponsoring agencies, NSF selects a panel of experts who will conduct the study. Administrative oversight of the panel is provided by Loyola College in Maryland, which operates JTEC under an NSF grant.

Panelists are selected for their expertise in specific areas of technology and their broad knowledge of research and development in both the United States and in Japan. Of great importance is the panelists' ability to produce a comprehensive, informed and unbiased report. Most panelists have travelled previously to Japan or have professional associations with their expert counterparts in Japan. Nonetheless,

as part of the assessment, the panel as a whole travels to Japan to spend at least one week visiting research and development sites and meeting with researchers. These trips have proven to be highly informative, and the panelists have been given broad access to both researchers and facilities. Upon completion of its trip, the panel conducts a one-day workshop to present its findings. Following the workshop, the panel completes its written report.

Study results are widely distributed. Representatives of Japan and members of the media are invited to attend the workshops. Final reports are made available through the National Technical Information Service (NTIS). Further publication of results is encouraged in the professional society journals and magazines. Articles derived from earlier JTEC studies have appeared in *Science*, *IEEE Spectrum*, *Wall Street Journal*, *New York Times*, and others. Additional distribution media, including videotapes, are being tested.

Over the years, the assessment reports have provided input into the policy making process of many agencies and organizations. Many of the reports are used by foreign governments and corporations. Indeed, the Japanese have used JTEC reports to their advantage, as the reports provide an independent assessment attesting to the quality of Japan's research.

The methodology developed and applied to the study of research and development in Japan has now been shown to be equally relevant to Europe and to other leading industrial nations. In general, the United States can benefit from a better understanding of cutting-edge research that is being conducted outside its borders. Improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit all our international partners in joint research and development efforts.

Paul J. Herer
National Science Foundation
Washington, DC

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EXECUTIVE SUMMARY

BACKGROUND

The Japanese have recognized that as we enter the "information age," both the computer industry and the television industry will need new display technology. The introduction of the laptop computer has created a need for a thin panel display with good readability and low power consumption. Television is entering a new era of high definition television (HDTV) or Hi-Vision, which the Japanese expect to be the first revolution in television since the introduction of color. The display is the major cost in HDTV sets, which require very large screens for the improved resolution to be appreciated. The new generation of computer workstations requires the same high-resolution performance as HDTV. Some Japanese companies are in both the television and computer businesses. They view the consumer television business as the high-volume market that will drive the cost of displays down, providing the critical display component for the new generation of computers that will make them competitive in the computer market.

The Japanese have recognized that new display technologies are critical to making their electronic products highly competitive in the world market. The cathode-ray tube (CRT) is rapidly losing market share to the solid-state, driven matrix flat-panel display (FPD). The Japanese estimate that by the year 2000, the sales volume of CRTs and liquid-crystal FPDs will be shared 50/50. The passive matrix liquid crystal display (LCD), the electroluminescent display panel, the plasma panel, and now the active matrix LCD are being introduced for computer and television displays.

During the 1980s, the Japanese electronics industry achieved worldwide preeminence in FPDs and, in particular, LCDs. This preeminence is due to their technical achievements and broad industry base in research, development, and manufacturing. This has been achieved almost completely within Japan, where there is industrial participation, government guidance, a larger domestic market end use, and a complete infrastructure.

The FPDs have made feasible new end-use products that have stimulated the entire electronics industry in Japan. Flat-panel displays have not been developed to replace CRTs but to expand electronic display applications where the weight, power, and volume of CRTs inhibit their use. Currently FPDs still cannot compete with CRTs in price and performance.

SUMMARY OF REPORT

The purpose of this study is to characterize the research, development, and manufacturing status of the Japanese FPD industry today, to predict how this industry will evolve during the 1990s, and to report the findings to the U.S. scientific and engineering communities. The JTEC committee, consisting of a group of six JTEC panelists (technical experts in display technology) and five observers, derived its information principally from its field visits to 33 sites in Japan in October 1991. To determine the depth of the FPD industry and the emphasis in LCDs, the committee visited industrial laboratories, supporting infrastructure, manufacturing facilities, and the Japan Electronics Show. To confirm its conclusions, the committee interviewed key technical leaders in government, industry, and universities and reviewed the literature.

The emphasis in the industry and in our study is on LCD panels. Approximately 90% of the LCD panels currently produced are passive matrix panels, which are used primarily for computer displays where high resolution, fast response time, grey scale, and high contrast are not essential. The performance of passive matrix displays has improved recently with the introduction of supertwisted nematic (STN) materials. However, active matrix LCDs (AMLCDs) provide much improved resolution, response time, grey scale, and contrast. While AMLCDs comprise only about 10% of current production, that percentage is growing rapidly. AMLCDs not only give improved performance for computer displays but, with the exception of cost and size, also meet almost all of the requirements for television displays, as long as the viewer is not too far off axis.

Future display needs will probably be met with a combination of types. For small displays--from 14- to 16- inch diagonals and eventually up to 20 inches--it is expected that LCD panels will dominate for the foreseeable future. At present this market is primarily passive matrix LCDs, but the higher performance AMLCD panel is rapidly expanding its share of the market. It is expected that the CRT will still dominate the market for sizes from 20 to 30 inches. For displays larger than this (as in HDTV displays), light-valve projectors using AMLCD panels are thought to be the near-term solution. In the longer term, NHK and several others expect plasma panels to be used for the long-sought-after "hang-on-the-wall" display panel. Although the scope of the GTC consortium has been reduced, its supporters still think that, in the long term, the AMLCD will be the "hang-on-the-wall" display.

Our study covers the range from basic research in materials to automated manufacturing technology. The JTEC panel is divided in its opinion about the relative levels of effort and productive output in Japan and the United States in basic research on display technologies. It is apparent, however, that most of the past contributions to basic display technology have come from the United States and Europe. The group is unanimous in its opinion that the long-term investment in

manufacturing technology and in manufacturing facilities in Japan is very impressive. In AMLCD manufacturing facilities alone, Japan's investment in the last few years exceeds two billion U.S. dollars.

In spite of the huge investment, there are still many manufacturing issues to be resolved. However, it is clear that for new matrix display technologies, Japan has the infrastructure to provide the long-term investment capital, manufacturing equipment, manufacturing technology, and all of the critical components to potentially dominate this market.

The panel feels that U.S. display technology is competitive in some areas and superior in others. However, without the long-term investment in manufacturing facilities and the resolve to lower manufacturing costs by addressing both the computer and the consumer markets, the United States will not be able to profit from its investment in display research. The relative status of the U.S. and Japanese display industries is shown in Tables Exec.1 and Exec.2. Table Exec.3 summarizes some conclusions.

The body of this report describes in detail the technologies being developed in Japan for the manufacture of FPDs. Chapter 1 gives an overview of the study results; Chapter 2 describes the materials infrastructure; and Chapter 3 describes the manufacturing infrastructure. Chapters 4, 5 and 6 discuss progress in FPD devices with an emphasis on LCD technology, in which the most progress has been made over the last ten years, and in which the Japanese are significantly ahead of the rest of the world. Appendix A summarizes the panel members' professional experience while Appendix B contains trip reports describing each site visit. Appendix C is a glossary of some of the specialized terminology used in this report.

Table Exec.1
Japan Compared to U.S. in Flat Panel Displays

	Research	Development	Production	Max Size
Passive LCD				
Super Twist	+ ↗	+ ↗	+ ↗	17" Japan
Ferro-LCD	○ ↗	+ ↗	+ ↗*	15" Japan
ECB	+ ↗	+ ↗	+ ↗*	14" Japan
Active LCD				
Metal-Insulator-Metal	+ ↗	+ ↗	+ ↗	13" Japan
Amorphous-Si TFT	○ ↗	+ ↗	+ ↗	15" Japan
Poly-Si TFT (Low Temp)	— ?	— ○	NONE	NOT KNOWN
Poly-Si TFT (Hi Temp)	— ?	— ○	+ ↗	10" Japan
Polymer Dispersed	— ↗	— ○	NONE	NONE
Emitters				
Electroluminescent	+ ↗	— ↗	— ↗	18" USA
DC Plasma Display	+ ↗	+ ↗	+ ↗	33" Japan
AC Plasma Display	○ ↗	○ ↗	+ ↗	31" Japan

+ = Japan ahead ↗ = Japan gaining ground

* The Japanese have announced production for late 1992

Table Exec.2
Comparison of Japanese and U.S.
Display Efforts

- Competitive in basic research and gaining
- Japan leading in product development and expanding
- Japan dominating in investment and implementation in manufacturing

Table Exec.3
Conclusions - Future Trends

- Japan has focussed primarily on direct-view LCD FPDs for the 1990s
 1. Amorphous-Si TFT LCD for 3" to 16" video performance in color
 2. Compensated STN LCD for 3" to 18" graphics performance
- FPD cannot compete in price with CRTs or high-end performance CRT
 1. The large, direct view, consumer TV or HDTV on-the-wall is not yet feasible before the year 2000
- LCD projectors are emerging to compete with CRT projectors
 1. Amorphous-Si TFTs and Poly-Si TFTs competing for market share
- EL and Plasma will be relegated to custom markets
 1. Color is needed to change trend

CHAPTER 1

FLAT - PANEL DISPLAYS IN JAPAN: AN OVERVIEW

Lawrence E. Tannas, Jr.

INTRODUCTION

By the mid-1980s it was becoming obvious to displays industry experts that the Japanese displays industry was beginning to make significant breakthroughs in technical development and manufacturing of liquid crystal displays (LCDs). This study is dedicated to observing the extent of these developments and to reporting them to all.

ORGANIZATION

This chapter summarizes the overall results of the study. The later chapters, written by other committee members who are experts in the industry, discuss the major areas of displays. The primary method of gathering information and data was making personal visits to individual Japanese companies from September 30 to October 12, 1991. The panel members, along with observers who assisted them, are listed in Tables 1.1 and 1.2, respectively. The companies visited by the combined committee of panel members and observers are listed in Table 1.3. A trip report for each visit is included as Appendix B to this report.

Table 1.1
JTEC Flat-Panel Display Technology Panel Members*

NAME	AFFILIATION
Lawrence E. Tannas, Jr. Co-chairman	President, Tannas Electronics Consultant in flat-panel displays and display device development
William E. Glenn Co-chairman	Professor and Director Imaging Systems Lab., Dept. of EE Florida Atlantic University Projection display development, display systems
Thomas Credelle	Manager, Portable Display Engineering Apple Computer AMLCD development, display systems
William Doane	Professor and Director Liquid Crystal Institute Kent State University LCD materials
Arthur H. Firester	Director, Display Research Lab. David Sarnoff Research Center AMLCD development
Malcolm Thompson	Manager, Electronic & Imaging Lab. Xerox Corporation AMLCD development

* See Appendix A for further details

Table 1.2
JTEC Flat-Panel Display Technology Committee Observers

NAME	AFFILIATION
Jerry Covert	Manager, Display Technology Group Wright Patterson AFB Avionics displays
Heidi Hoffman	Office of Computers & Business Equipment U.S. Department of Commerce Display analyst
James Larimer	Principal Scientist NASA Ames Research Center Image quality, display performance
Marko M.G. Slusarczuk	Manager, High Definition Display Technology Program, DARPA Display Research Director
Cecil H. Uyehara	President, Uyehara International Assoc. Consultant, U.S.-Japanese relations

Table 1.3
Japanese Sites Visited

Anelva Corporation (Fuchu-shi, Tokyo)

Manufacturer of thin-film deposition machinery

Asahi Glass Electronics, R&D Center Co., Ltd. (Yokohama-shi, Kanagawa)

Manufacturer of glass and LCD researcher
60% owner of Optrex
20% owner of Advanced Display, Inc.

Dainippon Ink and Chemicals, Inc., Central Research Laboratories (Sakura-shi, Chiba-ken)

Manufactures and researches LC materials

Dai Nippon Printing Co., Ltd., Central Research Institute

Manufactures color filters on glass and CRT shadow masks

DaiNippon Screen Mfg. Co., Ltd. (Toshima-ku, Tokyo)

Manufactures equipment for photoresists, screening, exposure, developing, etching, stripping, processing, and cleaning

DTI and Toshiba (Factory Visit) (Himeji)

Manufactures AMLCDs

Fujitsu, Organic Materials Laboratory (Morinosata-Wakamiya, Atsugi)

Manufactures PDPs and FVDs and conducts research on LCDs

HDTEC Corporation (Shinjuku, Tokyo)

Researches AMLCD projector for HDTV

Table 1.3 (Continued)

Hitachi, Ltd., Hitachi Research Laboratory (Hitachi-shi, Ibaraki-ken)

Researches, develops, and produces LCDs

Hosiden Corporation (Nishiku, Kobe-City, Hyogo)

Met at New Otani Hotel
Manufactures STNs and AMLCDs

IBM Japan, Ltd. (Yamato-shi, Kanagawa-ken)

Researches and develops AMLCDs

Japan Electronics Show '91

Nippon Convention Center (Makuhari Messe)

Matsushita, Display Technology, Research Laboratory

Researches, develops, and manufactures AMLCDs

Merck Japan, Ltd. (Aikawa-Machi, Aikou-gun, Kanagawa Pref.)

Manufactures and formulates LCD materials

Ministry of International Trade and Industry (MITI) (Kasumigaseki, Tokyo)

NEC Corporation, Display Device Research Laboratory (Miyamae-ku, Kawasaki,
Kanagawa)

Manufactures LCDs

NHK, Science and Technology Research Laboratory (Tokyo)

Researches PDPs

Nippon Electric Glass Co., Ltd., Technology Division (Otsu, Shiga)

Manufactures display glass

Table 1.3 (Continued)

- Nippon Telegraph and Telephone Corporation (NTT) Interdisciplinary Research Laboratory** (Musashino-shi, Tokyo)
 Researches AMLCDs
- Sanyo, Tottori Sanyo Electric Co., Ltd., Electronic Device Business Headquarters** (Tachikawa-cho, Tottori City)
 Manufactures LCDs
- Seiko-Epson Corporation** (Suwa-shi, Nagano-ken)
 Manufactures most forms of LCDs
- Sharp Corporation - Factory Visit, Nara Plant and Tenri Plant** (Minosho-cho, Yamatokoriyama, Nara and Ichinomoto-cho, Tenri, Nara)
 Manufactures TSTNs and a-Si TFT LCD
- Sharp Corporation - R&D Visit** (Ichinomoto-cho, Tenri, Nara)
 Researches and develops EL and LCD forms of FPDs
- Sharp Corporation - Showroom Visit** (near Ichigaya Station on Chuo Line)
 Demonstration of Sharp LCDs, computers, and consumer products
- Sony Corporation Research Center** (Kitashinagawa, Shinagawa-ku, Tokyo)
 Researches, develops, and manufactures AMLCDs
- Stanley Electric Co., Ltd, Research and Development Laboratory** (Yokohama-shi, Kanagawa-ken)
 Researches and develops AMLCDs
- Tohoku University--Professor Tatsuo Uchida**
 (Met at Ginza Daiichi Hotel)

Table 1.3 (Continued)

Toppan Printing, Co., Ltd. Electronics Division (Chuo-ku, Tokyo)
Manufactures color filters for LCDs

Toshiba Corporation, Electronic Device Engineering Laboratory (Isogo-ku, Yokohama)
Researches, develops, and manufactures LCDs

Tottori University—Professors Hitoshi Kobayashi and Shosaku Tannaka, and the Dean of Engineering, Muneo Oka (Koyoma, Tottori)
Researches electroluminescent technology

Tokyo University of Agriculture & Technology—Professor Shunsuke Kobayashi (Tokyo)
Researches LCDs

University of Hiroshima—Professor Heiju Uchiike (Met at Sharp Showroom and DNP)
Conducts research on PDPs

OBJECTIVES OF THE COMMITTEE

The following objectives were drawn up at the committee's organization meeting.

Preamble. It is recognized that, during the 1980s, the Japanese electronics industry achieved worldwide preeminence in electronic information flat-panel displays (FPDs). This preeminence is due to their technical achievements and broad industry base in research, development, and manufacturing. This has been achieved almost completely within Japan, where there are industrial participation, government guidance, end-use markets, and a complete infrastructure.

The FPDs have made feasible new end-use products that have stimulated the entire electronics industry in Japan. Flat-panel displays have not been developed to replace the cathode-ray tubes (CRTs), but rather to expand electronics display applications where the weight, power requirements, and volume of the CRT inhibit its use.

In Japan, electronic displays are a key element for the new age, which the Japanese call the *information society*. Display technology development has been accelerated because of the technical emphasis in the Japanese culture and the desire for greater communications through visual imagery. It is recognized that, today, the leading FPD devices are based on LC technology. The technical emphasis is to achieve higher resolution in larger size with full color and at video speeds. The marketing need is to develop a high-information-content (HIC) FPD at lower cost.

Purpose. The purpose of this study is to characterize the research, development, and manufacturing levels of the Japanese FPD industry as it exists today and to ascertain how the Japanese believe the industry will evolve during the 1990s.

The committee was tasked with identifying the key technical limitations in materials, implementation, and expertise that may inhibit the evolution of the various FPD technologies. Secondly, the committee was to identify the key market and end-use product objectives that motivate and drive the evolution of FPDs.

Approach. The committee was to:

- o Derive its information principally from review of the literature and field visits in Japan. The travel to Japan was a key element in determining the depth of work and emphasis.
- o Review the accomplishments exhibited at the Japan Electronics Show and end-use products exhibited in the marketplace and company showrooms.
- o Determine technical depth by visiting industrial laboratories, supporting infrastructure and manufacturing facilities, and by reviewing the literature.
- o Determine evolution of the industry by interviewing key technical leaders in government, industry, and universities and by reviewing the literature.

Because of limited resources and obvious industry activities, the study concentrated on LC technologies and all their ramifications.

MAJOR TECHNICAL FINDINGS

As a result of its study the committee observed several major areas that show the direction and extent of the maturity of FPDs in Japan:

- o Depth and extent of development of LCDs
- o Commitment to production of LCDs
- o Changing consensus in large FPDs
- o Changing role of electroluminescent (EL) displays and plasma display panels (PDPs)
- o Infrastructure in Japanese FPD industry
- o Market and projected sales
- o New a-Si Active Matrix (AM) LCD factory
- o Emphasis in the 1990s

During the 1970s and 1980s, all of the flat-panel technologies were developing on a relatively broad front in the United States, Europe, and Japan. However, because of cross-coupling (Tannas, 1985), LCD technology could not be applied to large arrays such as are required for television and computers. The contrast and viewing angle were degraded by a so-called *sneak circuit* between picture elements (pixels) turned on and those intended to be left off. This effect can be minimized with AMLCDs, in which diodes, field-effect transistors, or other nonlinear elements are constructed at each pixel. In the United States, the cost of such an LC FPD has been considered prohibitive; but several Japanese companies have perfected techniques to mass-produce AMLCDs for HIC displays, to add color, and to improve viewing angle performance.

In parallel to the active matrix approach, a concerted effort was applied to passive matrix LCDs. A series of developments has rendered the super-birefringent form of LCD manufacturable with wide viewing angle and in black and white monochrome, as well as color. This form of LCD, called *compensated supertwist*, possesses sufficient nonlinearity for manufacturing of HIC computer displays. As yet, it does not possess sufficient speed or color for television video.

In the United States, by comparison, there has been limited research and development on AMLCDs and supertwisted nematic (STN) LCDs. At present, there are activities at Sarnoff Research Laboratory, Xerox PARC, and OIS Optical Imaging Systems on AMLCDs and at Standish and Tektronix on STN LCDs.

The development of successful techniques to matrix-address large arrays of LCDs during the 1980s is bearing fruit in the 1990s. The successful production of colored AMLCDs and low-cost STN LCDs in Japan has changed the entire picture in the

FPD industry. It appears that, out of all the FPD technologies, the LCD will dominate through the 1990s; it also appears that the other FPD technologies, such as EL, plasma, light-emitting diodes, and so forth, will be relegated to custom markets.

EXTENT OF DEVELOPMENT OF LIQUID CRYSTAL DISPLAYS

All the leading forms of LCDs are under research and development in Japan. In all the major LCD areas, Japanese companies have made fully functional prototypes representing the most advanced product demonstrators to be found in the world. Table 1.4 lists the leading examples.

The predominant AMLCD technology is the amorphous silicon thin-film transistor (a-Si TFT). One low-mobility field-effect transistor is used at each addressable dot where the row line is connected to the gate electrode for synchronization and the column line is connected to the source electrode, and where the active area of the pixel is connected to the drain. Several forms of the TFT are used. Typically a storage capacitor is used at each pixel for improved performance.

Most manufacturers believe that the a-Si TFT LCD has become the approach of choice for the AMLCD. It has good gray shades and color, fast response, and a wide viewing angle. Manufacturing machinery has been developed to make displays 15 inches in diagonal.

The latest accomplishment has been to significantly improve the viewing angle. Two of the techniques for doing this are as follows:

- 1) Control the optical retardation in all three display axes by adding a retardation film. The film is designed with reduced birefringence in the axis away from the normal to compensate for the increased optical path length of the display cell when viewing it away from the normal. The conical retardation films possessing these properties are manufactured by Nitto Denko.

- 2) Divide the pixel electrode into subpixels for half-tone/gray-scale method of achieving a wide viewing angle. The voltage is varied between the subpixels by a capacitor divider circuit. Thus, the LC material is at different states of rotation at each subpixel and exhibits an effective wider viewing angle for the complete pixel. An AMLCD with this feature has been successfully built and demonstrated by Hosiden.

The second high-performing AMLCD uses poly-silicon (p-Si) TFT LCDs. Poly-silicon is very similar to a-Si except that it is deposited and annealed at a temperature

Table 1.4
Largest LCD Prototypes

	SIZE (INCH DIAG.)	ROWS	COLUMNS	COLOR	COMPANY	
A. Active Matrix	15	900	1152x3	Color	Matsushita Elect. Ind. Co.	
						1. TFTs a-Si
	10 ⁺	TBD	TBD	TBD	Seiko-Epson	
2. MIM	13	960	1480	B/W	Seiko-Epson	
B. Passive Matrix	16.7	780	1120	B/W	Sanyo	
						1. Compensated STN
						2. ECB*
3. FLC	15	960	1312	B/W	Canon	
FLC	15	512x2	640x2	Color	Canon	

* Research Only

* Incorporates the French Super Homeotropic LC Array System

above 600°C to give it quasi-crystalline structure and higher mobility. This technology is usually made on quartz substrate and fabricated on a metal-oxide semiconductor (MOS) line. Production machinery for large substrates has not yet been developed. The primary motivation for poly-Si TFTs is that they have the mobility and speed for the peripheral row and column drivers and shift registers; therefore, they can be made at the same time and on the same substrate as the pixel TFTs. Additionally, the smaller substrate of an MOS line allows for smaller design rules for the circuits and higher resolution displays. These two features--higher mobility and higher resolution--make p-Si LCDs most suitable for LC projector displays and LCD viewfinders for camcorders.

Because of the high process temperature, the p-Si LCD has not gone into large-volume production for large displays (over five inches diagonal) in Japan. Seiko-Epson and others are developing a low-temperature (below 600°C) p-Si process. In the meantime, Seiko-Epson, Sony, and others continue to manufacture p-Si TFT LCDs for the higher performance, higher cost, smaller size applications.

A third AMLCD technology is metal-insulator-metal (MIM) diodes. At each pixel the MIM diodes are fabricated as a nonlinear device to prevent cross-coupling. This approach is less expensive than TFTs and gives better performance than the low-cost passive LCDs. Seiko-Epson and Toshiba have this LCD technology in production.

Several LCD passive technologies are either in production or are being developed for production. In Japan, the most successful display uses the STN technology; in 1991, over six million monochrome STN displays were made there for computers and word processors. It is the first HIC, low-cost display that could be made with acceptable performance. The speed is too slow for video, and the color is limited. However, the contrast and viewing angle is better than in its predecessor, the twisted nematic (TN) LCD. Almost all the Japanese displays manufacturers--led by Sharp, Toshiba, Hitachi, Sanyo, Seiko-Epson, Matsushita, and others--make STN LCDs. The performance of the STN has been improving, with innovations such as double cells and film, optically compensated displays for black-and-white images, with color filters as in AMLCDs for color, and further, with retardation films for wider viewing angles and better transmittance. One product is the Sharp triple-layer STN, which uses a retardation film on the top and the bottom of the STN LCD cell. An early (1988) high-brightness STN black-and-white display was the Toshiba M-ST LCD, which used one compensating film and one STN cell (Model TLX-1501-C3M).

Another passive LCD approach, called *electrically controlled birefringence* (ECB) was developed by Stanley using a French research concept in a joint developmental effort. The ECB LCD has the advantage of a wide viewing angle and the disadvantage of slow speed of response.

A third passive LCD approach using bistable ferroelectric LCDs (FLCDs) has been developed by Canon. It has the advantage of image storage and the disadvantage of slow addressing speed.

Several Japanese companies have started research projects using polymer-dispersed LC (PDLC) material. The PDLC requires an active matrix addressing technique. Here, the advantage is high transmittance, because the PDLC, unlike the other LCDs, does not use polarizers. It scatters light when at rest and transmits light when energized. Therefore it is best-suited to projector displays.

Magnitude of Research and Development

The Japanese electronics industry has a high interest in developing FPDs for new industrial and consumer products. Scientists at Nippon Telephone and Telegraph (NTT) estimated that more than ten industrial research laboratories and more than ten government, university, and utility company laboratories have research projects devoted to LCDs. These laboratories have engaged more than one thousand engineers and scientists to work on LCDs alone.

COMMITMENT TO PRODUCTION OF LIQUID CRYSTAL DISPLAYS

Both the STN LCDs and the a-Si AMLCDs have advanced to high levels of production. The lower cost STN LCD is used in word processors and computers, and the higher cost, higher performance a-Si AMLCD is used where video speeds and full color are needed.

Between these two technologies in cost and performance is the MIM technology, also in production and in the marketplace. Most Japanese displays companies are committed to high-volume STN LCD and a-Si AMLCD production. In Japan, it is felt that STN LCDs (and derivatives using compensators and retardation films) and a-Si AMLCDs will be the dominant FPDs throughout the 1990s. They are expected to compete for market shares, with low cost on the one end and high performance on the other. The MIM approach will compete as a price/performance compromise between the lower cost STN LCD and the higher performing a-Si AMLCD.

The other LCD approaches have not reached significant production comparable to STN, MIM, and a-Si AMLCDs. The ECB and FLC displays have not yet been put into production; however, two companies, Stanley and Canon, expect production within a year.

The magnitude of investment made by various companies in STN LCDs and a-Si AMLCDs exceeds any such commitment ever made in the history of flat-panel displays. Table 1.5 tabulates various company project announcements. The table

Table 1.8
Investments in AMLCD Factories in Japan

Maker	Plant Name	Start Date	Diagonal Size (inch)	Maximum Capacity (1000/mo)	Application	Investment Billion Yen Excluding land
Sharp	Tenri	1986	3-6		Video	14
	New Tenri	April 1991	6-10	5 time	Video & Computer	27
	Mie	Aug 1993	Over 10		Video & Computer	40 in 92 1st station
DTI (Toshiba 50% IBM 50%)	DTI	May 1991	Over 10	42 1st stage	Computers (internal use)	20 IBM 20 Toshiba
Hitachi	Mobara, old line	Oct 1988	5 and 10.4	4	Video & Computer	10
	Mobara, new line	Under study	10 and 12.5		Computers	Not decided
Hosiden	Development Technology Laboratories	Oct 1987	3 to 10	60	Computers and avionics	45 equivalent in 1991 money
NEC	Tamagawa (R&D Pilot Line)	Mid 1986	4.3 to 9.3	2		6
	Kagoshima	Aug 1990	4.3 to 9.3	20		10 1st stage
Matsushita	Ishikawa	March 1991	10	5		40 1st stage (15 for building)
Mitsubishi (Asahi Glass 10%)	Kumamoto	Mid 1992			Computers	20
Selko Epson Suwa		Operating			Video and projectors	10 for MiM and poly Si

Source: Nikkei Electronics Flat Panel Displays of 1990 1989-11-1 and updates by Tannas Electronics

Total: 272 Billion Yen
or \$ 2 Billion U.S.

is not definitive as to when the investments are made and what portion of the investment is in land and buildings; it is more important from the standpoint of the total announced projects and the companies involved. Conservatively, the amount totals over two billion U.S. dollars.

Production Size

In size, LCDs are limited to approximately 15 inches by the size of the substrates, electronic line driver issues, and cross-coupling in the row and column display matrix. There have been evolutionary improvements in STN, MIM, and a-Si AMLCD electronic line drivers and cross-coupling such that video graphic adapters (VGA) (640 x 480 lines) and television resolutions are in production in 1991 and will improve as the computer and television industries move to higher resolution.

The physical size of the LCD is limited by machine substrate size. In Japan, the LCD production machine industry has just developed the capability to process substrates nominally 320 mm x 400 mm. This development has been extremely expensive; the major production machines used for making a-Si TFTs typically cost over one million U.S. dollars each.

The sentiment in the LCD manufacturing industry is that a new era of electronic production has arrived, that is, three-micron design rule on printed circuit board-size substrates. New lessons in production processes, production machinery layout, materials handling, and so forth need to be learned. This generation of machinery must pay for itself before the next quantum size change can be considered. As a consequence, the next significant size change, particularly for AMLCDs, may not occur until the year 2000.

CHANGING CONSENSUS IN LARGE FPDs

Throughout the world, from the beginning of video displays, researchers have aspired to make a large "picture-television-on-the-wall" flat-panel display. In the Japanese displays industry and others, this desire was heightened with the advent of high definition television (HDTV).

In Japan, with funding from Japan Key Technology Center (JKTC) and sponsorship from the Ministry of International Trade and Industry (MITI), a consortium of companies called "Giant Technology Corporation" (GTC) was organized in 1989 to make a one-meter AMLC FPD by 1994 (Elkus, 1991). This activity was highly publicized and highly politicized. The technical approach was to make a p-Si AMLCD using printing techniques instead of optical means for defining the circuits.

The GTC program has made significant progress in researching the printing technique. However, because of technical difficulties and significant budget cuts, it is no longer committed to making a one-meter panel as originally proposed.

Another project is being organized to make a large, one-meter HDTV plasma panel. This activity is expected to succeed where the AMLCD did not. The rationale is that plasma panels are already made by low-cost printing or screening techniques and that plasma phosphors are already developed, whereas the low-temperature p-Si process required for AMLCD is not.

It is anticipated that GTC will continue research on process technologies for the one-meter p-Si AMLCD with reduced expectations and that a renewed effort will continue, possibly with the formation of a new consortium like GTC, to develop a one-meter plasma panel for HDTV.

Another consortium, called HDTEC, sponsored by the Ministry of Post and Telecommunications (MPT) and founded by JKTC, is directed at developing a large-screen projector for HDTV using p-Si TFT AMLCD light valves. This consortium is making significant progress (Yokozawa, 1991).

Both direct-view and projection technologies are being developed for large-screen (over 40 inches in diagonal) consumer and industrial HDTV. The projection technologies using CRTs and LCD light valves are now available in limited production. The leading producer is Sharp, which uses a-Si TFT LCD light valves with peripheral row and column drivers attached via TAB polyimide carriers.

Neither during the Japan trip nor while examining the literature did we observe sufficient activity to indicate that a direct-view FPD will be available, in production, before the year 2000. It still appears that the market for large-screen televisions will be served by both front- and rear-projecting CRTs and LCDs, which will compete for market share. Within the LCD approach, a-Si TFT and p-Si TFT LCDs will compete for market share.

CHANGING ROLE OF ELECTROLUMINESCENT DISPLAYS AND PLASMA PANELS

The roles of EL displays and plasma panels are changing because of their lack of full color. In the case of EL, suitable phosphors have not been demonstrated. In the case of plasma, suitable phosphors have been available, but, because of the plasma/UV excitation of the phosphor, there are problems in terms of life, efficiency, and background illumination from Hg visible line emissions. The production of LC HIC FPDs now exceeds the worldwide production of plasma panels by over an order of magnitude and the production of EL displays by two orders of magnitude.

Several companies such as Fujitsu, Hitachi, NEC, and NTT have stopped R&D on EL. Also, NEC and DNP have stopped production on plasma panels.

The proponents of these two technologies point out that they have several advantages over LCDs that will ensure their continued use. Both technologies are used in the custom marketplace, have existing factory capacity, will benefit from product inertia and reputation, and offer wide viewing angle, self-luminance, and fast response. Electroluminescence is made in the thinnest form factor, and plasma is made in the largest form factor. NHK is presently making 33-inch full-color experimental plasma panels with HDTV resolution.

Until the primary problems with both techniques--cost and lack of full color--are solved, these two technologies will lose FPD market share. At the Japan Electronics Show '91, no demonstrations indicated that these techniques were making any significant advances in color.

In spite of the lack of color, the manufacturers (Sharp in the case of EL and Matsushita in the case of plasma) predict a growth in production volume. EL is considered to be most suitable for the industrial and computer workstation market because of its wide viewing angle, brightness, ruggedness, and high information content. Plasma is unique in being the largest FPD in size, and it is considered to have the greater promise as a full-color display.

INFRASTRUCTURE IN JAPAN'S FPD INDUSTRY

During the field trip to Japan, the committee visited the glass, chemical, printing, and machinery industries that support the LCD industry, as well as the Japan Electronics Show '91, where new consumer products were seen. It was clear that there exist within Japan the elements of the complete business cycle--display panel material; display production machinery; factories for LCD, EL, plasma, and so forth; and an end-use market. Additionally, almost all the peripheral electronic and display-based product electronics are made in Japan. The only exceptions of note are that approximately 70% of the basic LC materials are manufactured in Europe, and approximately 90% of the a-Si TFT glass substrates and EL glass substrates are manufactured in the United States by Corning. Corning has announced that it will build a glass factory in Japan.

The end-use products for HIC FPDs include hand-held televisions, word processors,¹ computers, (Sony) Data Discman,² and picture telephones. Each complete product is made in Japan.

Additionally, the production of FPDs is not completely vertical within a company. A typical example is the a-Si TFT AMLCD made by Sharp. A schematic diagram of the display fabrication/assembly process is shown in Figure 1.1. The TFT substrate is made at the Sharp factory in Tenri. The color matrix substrate is made by an unidentified Japanese printing company and is shipped to Sharp, where it is combined with the TFT substrate and filled with LC material. The large-scale integration (LSI) drivers on tape-automated bonding (TAB) are made at another Sharp factory. The completed panel and drivers are shipped to subcontractors for final assembly. The completed display, for example, may then be shipped to Hitachi for assembly into an end product such as the Sony Watchman and shipped to Sony for distribution and sales.

MARKET AND PROJECTED SALES

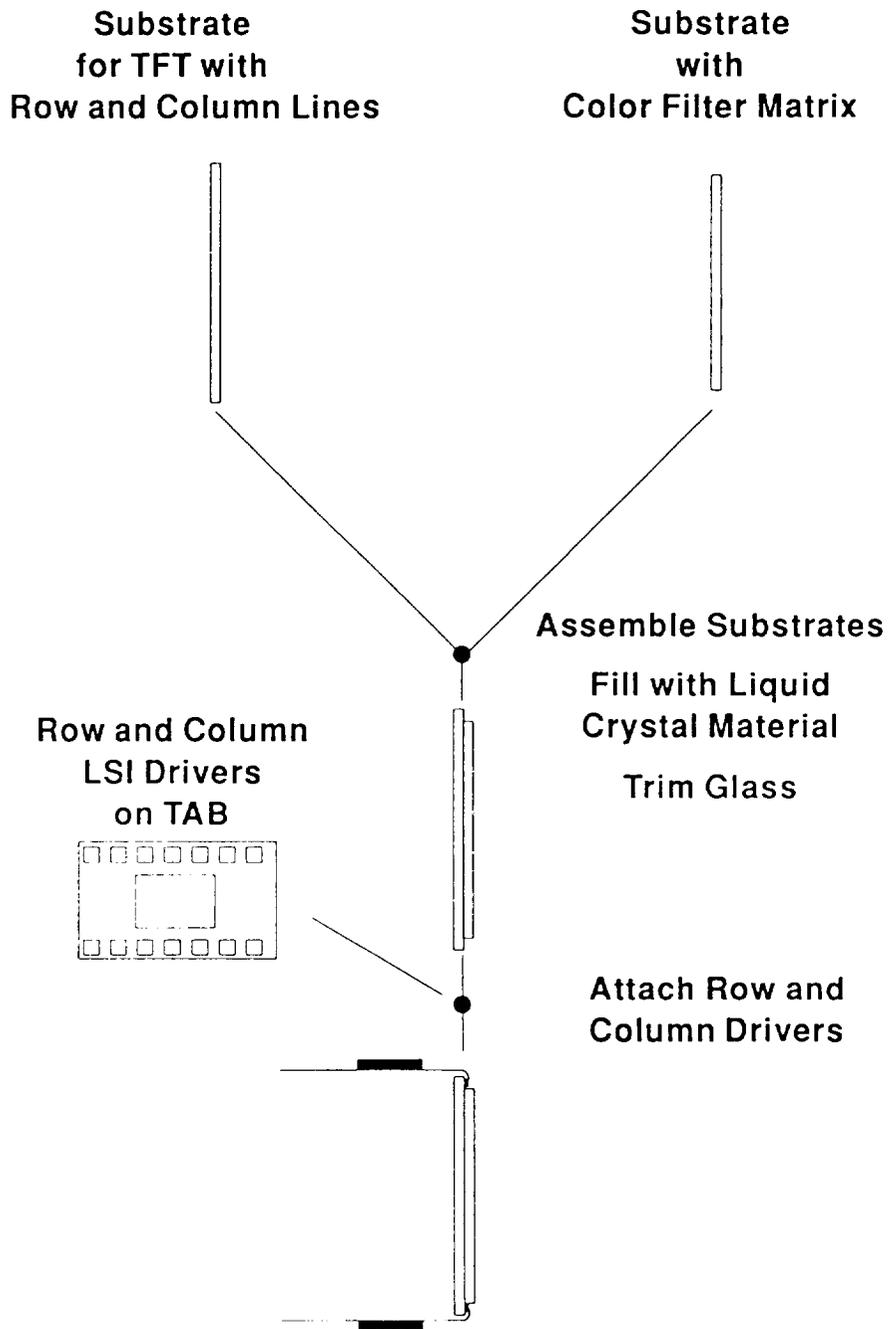
Hitachi's forecast of the FPD market size is summarized in Figure 1.2. There are several important summary comments to accompany this figure:

- o The display sales will double in 10 years, a 7% compounded annual growth.
- o Because of cost differential, CRTs will not be replaced by FPDs.
- o CRT sales will continue to grow, but at a slower rate than FPDs.
- o By the year 2000, half of the display sales will be in FPDs.
- o The portion of FPD market share captured by AMLCDs and passive LCDs is highly dependent on the technical evolution of those two approaches and the consumer product end market demand.

There was no evidence or market plan to indicate that the flat-panel "television-on-the-wall" at consumer prices would arrive before the year 2000. It is ironic that,

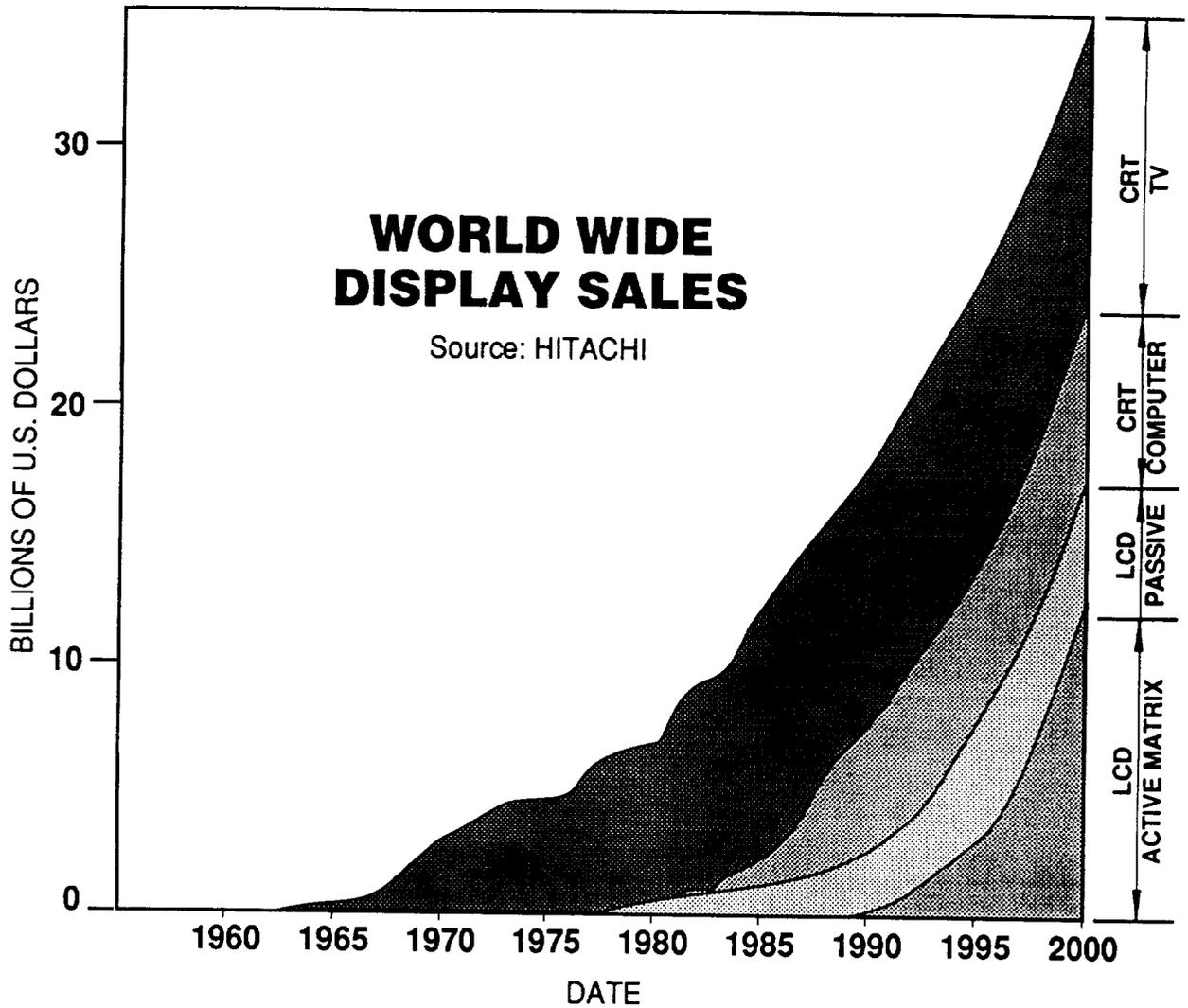
¹Often used in Japan as translators from Roman and Japanese Kana characters to Kanji characters.

²Sony sold 60,000 units in the first six months of the product.



Prepared by Tannas Electronics

Figure 1.1. Major Elements of Color Active Matrix LCD



- Displays Market will double by the year 2000
- CRTs will not be replaced by FPDs
- Half of the Display Sales will be FPDs by year 2000
- Market for FPDs is not satisfiable
- No consumer FPD TV on-the-wall

Figure 1.2. World Wide Display Sales

since the 1950s, the "TV-on-the-wall" has been the principal market motivation to develop FPDs, and it is still not technically feasible at a competitive price when compared to the conventional CRT.

The LCD market share breakdown for 1990 is as shown in Figure 1.3. The a-Si TFT AMLCD was not in significant production in 1990. Factories to produce the technology are just starting to come on line. By 1991, Sharp's monthly production rate was as follows:

Nara Plant

10 million	TN LCDs for calculators
350,000	STN LCDs for graphics
12,000	EL displays for machine control

Tenri Plant

150,000	a-Si TFT AMLCDs for TV and computer
40,000 (Projected)	a-Si TFT AMLCDs (new line starting 1/92)

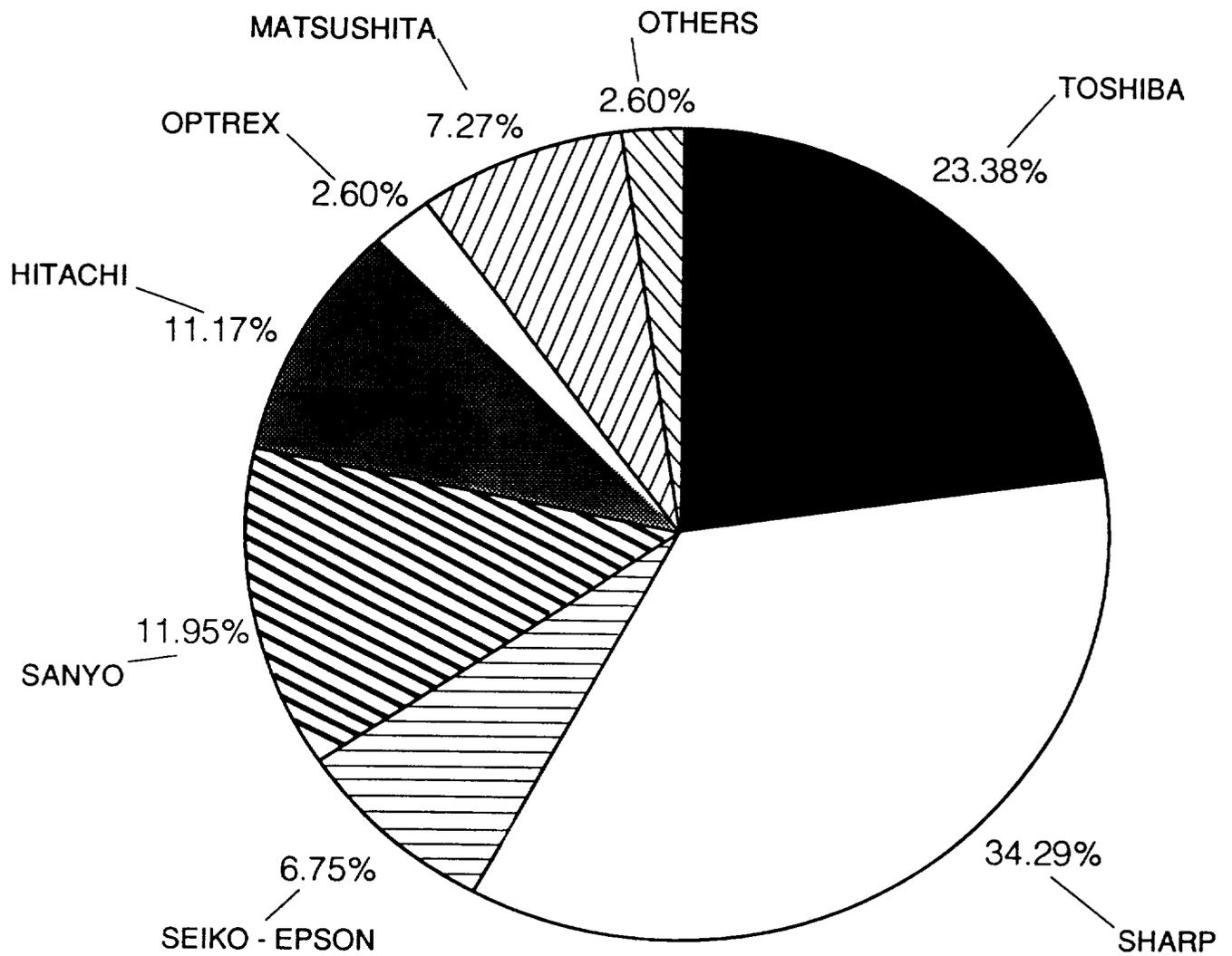
NEW a-Si AMLCD FACTORY

The description of the new Sharp a-Si AMLCD factory in Tenri offers insight into the vigor and magnitude of the displays industry in Japan. A similar scenario was relayed to the committee during the visit to the DTI plant built jointly by Toshiba and IBM Japan in Himeji.

Sharp has a complete product line of a-Si AMLCDs of the following sizes:

<u>Diagonal in Inches</u>	<u>Rows</u>	<u>Columns</u>
3"	234	382
4"	234	479
5.7"	240	720
8.4"	480	640 x 3
8.6"	456	960
10.4"	480	640 x 3

(Large Size LCD Module)



SOURCE: TOSHIBA MARKETING & SALES DIV.

Figure 1.3. 1990 Market Share

All of these displays have RGB color with fluorescent backlight modules. They are available with several controller chip designs to accommodate interfaces with NTSC, PAL, VGA, and so forth.

The new factory at Tenri is in a new building designed specifically for a-Si TFT AMLCDs. It is located on a site next to the existing a-Si factory. This existing line was the test bed for the new factory and is set up in a building previously used for LSI chip production.

The new line is going into the first floor of the new multistory building. It was scheduled to start operation in January 1992. The JTEC displays committee members were the very first outsiders to see the factory. The committee saw the factory while the equipment was being installed. The area is separated into Class 10, 100, and 5,000 clean zones for corresponding requirements in the product process. The line is used to make the a-Si TFT substrate, to combine it with the color filter substrate shipped from an outside vendor, and to fill it with LC material. The attachment of the row and column drivers and the backlighting is done by a subcontractor at another location.

Design capacity is 40,000 yielded displays per month, and yield is expected to be over 90%. It is expected that it will take several years of operation and learning to achieve design yield. The plan is to manufacture displays for notebook and lap-top PCs and large workstation-size displays.

It is estimated that over \$100 million worth of custom-made machines were being installed at the time of the visit:

- o PE CVD with load locks
- o sputtering with load locks
- o steppers
- o resist applicators
- o developers

Similar machines were grouped together, and cassette-to-cassette substrate carriers were used, requiring manual transport from machine to machine. The substrate size is about 12" x 15", which would accommodate two 10" displays or one 14" display per substrate. The arrangement allows for maximum flexibility in process flow. A major machine can be out of service for repair or cleaning without interrupting the flow.

All of the major support facilities, such as vacuum pumps, air conditioning and filtering, gas supplies, deionized (DI) water, and so forth, and a complete quality-control laboratory with test chambers, scanning electron microscopes (SEMs), and analytical equipment, are in the large basement.

The useful life of this new line was stated to be three to five years. This new line will also be used in designing the next line, planned for the second floor, and the following line, planned for the third floor. Sharp is already planning to build its next factory in Mie Prefecture.

It has been reported in the Japanese technical newspapers that by 1995 the Japanese displays industry may have a production capacity of one million AMLCDs per month.

EMPHASIS IN THE 1990s

In Japan, the stage is nearly complete for the production of FPDs through the end of the 1990s. No technical or manufacturing activity has been announced in the rest of the world that may significantly alter the direction that the Japanese displays industry is taking. The LC FPD industry is now orders of magnitude ahead of the other FPD technologies. The research, development, and production activities in Japan are so focused on LCD technology that funding for advancing EL, plasma, and other FPD technologies is diminishing. We are clearly in a new age in the evolution of FPDs, and, in Japan, LCDs are perceived as clearly being the leading technology. The cost and complexity of the new a-Si LCD factory are so extensive that the machines of the next generation of larger size will not be attempted until the present generation of machines have completely proven out and been paid for.

SUMMARY

In summary, the committee made the following general observations:

- o Japan has focused on LC FPDs for the 1990s:
 - a-Si TFT LCD for 3- to 15-inch video performance in color.
 - Compensated STN LCD for 3- to 18-inch graphics performance.
 - Large, direct-view, consumer-priced "TV-on-the-wall" is not feasible before the year 2000.
 - Research and development will continue but will be heavily weighted in the direction of LCDs.

- o FPDs cannot compete in price with CRTs.
 - For the first time, a-Si TFT AMLCDs have demonstrated performance comparable to CRTs in the 3- to 15-inch size.
 - The price separation between LCDs and CRTs for comparable performance will remain a factor of five to one or more.
- o LCD projectors are emerging to compete with CRT projectors in the 40- to 100-inch range:
 - a-Si TFTs and p-Si TFTs are competing with each other for market share.
- o EL and plasma will be relegated to custom markets.
 - Color improvements and cost reduction are needed to change the trend.
 - Because of unique performance attributes, each may increase in production volume where faster response time, wider viewing angle, and larger sizes are needed over the LCD achievements.

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CHAPTER 2

MATERIALS FOR FLAT-PANEL DISPLAYS

J. William Doane

INTRODUCTION

Advances in flat-panel display technology, as in many technologies, are largely driven by the discovery of new or improved materials. The electroluminescent (EL) display, for example, would capture a larger share of the market today if there were a more suitable blue or white EL phosphor available to provide a full-color display. Professor S. Kobayashi of Tokyo University of Agriculture and Technology points out that liquid crystal materials possess characteristics that allow them to meet basic criteria for a display: good viewability (legibility, full-color capability, gray scale, view angle); low-cost driving circuits; high information content resolution; low production costs; and light weight. This is perhaps the reason for Japan's multibillion dollar investment in liquid crystal displays (LCDs). There are still many material problems with LCDs. For example, Professor Kobayashi further points out, there remains a need for materials that will give a front-lit passive display. Nearly all of the manufacturing investment in Japan is for backlit displays; and in many ways, use of a backlight defeats the purpose of the passive liquid crystal material.

One of the goals of this study was to determine what Japanese scientists and industrialists consider to be principal limitations in display materials and to identify efforts to overcome these limitations. Because of the massive effort in LCD production and because the JTEC panel was made up primarily of experts in the LCD field, this review is heavily weighted toward LCD materials. These materials will be discussed first.

LIQUID CRYSTAL MATERIALS

Introduction and Historical Overview

Liquid crystal materials were discovered in 1888 by an Austrian botanist, F. Renitzer (Kelker, 1988), but only in the last 25 years have these materials been developed sufficiently to be used in electronically driven displays (Bahadur, 1983). In the early 1960s, when RCA was first considering using liquid crystals for dynamic scattering displays, a room-temperature nematic liquid crystal did not exist. The first room-temperature nematic phase was observed in the compound MBBA, but the temperature range was short and strongly affected by impurities (Demus, 1988). It was then discovered that eutectic mixtures of MBBA with other compounds in its homologous series could broaden the temperature range to extend from below -40°C to over 100°C . However, these mixtures were very unstable, and they also possessed a negative dielectric anisotropy not useful in the twist cell.

It was therefore a major breakthrough when cyanobiphenyl materials discovered by Professor George W. Gray of Hull University in England were found to exhibit room-temperature nematic phases. These materials were not only more stable, but they also possessed a large positive dielectric anisotropy and strong birefringence nearly ideal for the twist cell, which had been invented only a few years earlier. Patents on these materials gave English and European industries a leading edge in the manufacturing and marketing of nematic materials for displays. E. Merck of Darmstadt and F. Hoffmann-LaRoche, Ltd. of Basel remain leading suppliers of nematic materials today. Both companies have established divisions or joint ventures in Japan: Merck-Japan and RODIC, the latter name an acronym derived from Hoffmann-LaRoche and Dainippon Ink and Chemicals, Inc. The cyanobiphenyl patents are due to expire around 1993.

During the 1970s and 1980s, nematic liquid crystal compounds and mixtures for displays were developed primarily by industry. Almost totally disconnected from this effort were very strong research programs on liquid crystal materials in colleges and universities around the world. These programs explored not only nematic phases but also other kinds of liquid crystal materials, studying both the physics and the chemistry of the materials. In fact, the 1991 Physics Nobel Laureate, Pierre-Gille de Gennes, performed his prize-winning work on liquid crystals during this time. Out of this work came many new kinds of materials and liquid crystal phases, some of which have found applications in displays. One is the ferroelectric chiral smectic (FLC) phase. The pure smectic C was discovered at Kent State University (Saupe, 1969). Chirality was later added by R. Meyer (Meyer et al., 1975), and the resulting material was discovered to have a unique form of ferroelectricity. Noel Clark and S. Lagerwall (Clark & Lagerwall, 1980) patented an FLC display using this technology. Other examples are some forms of polymer dispersions that have links

to basic research programs in the university environments. Currently, new effects, such as the electroclinic effect, are being studied for display applications.

Japan has a strong display manufacturing capability and the associated infrastructure; now, with the leadership of such professors as S. Kobayashi in university circles, it is developing strong material research components. New, important materials are being discovered there. An example is the retardation film, which is extremely important for supertwisted nematic (STN), twisted nematic (TN), and other displays. This is truly a Japanese invention and is currently produced only by Japanese industry. From *Chemical Abstracts* it can be noted that Japanese scientists lead those in the United States and Europe combined by a ratio of 3:1 in applications for patents on liquid crystal materials for displays. U.S. and European researchers show much less awareness of or concern about applying liquid crystal materials in displays. Much of the new chemistry is published immediately in the open literature. The development of polymer liquid crystals (PLCs) is perhaps an example of this. Many new PLC materials are developed everyday that could be of value in the display industry if polymer workers were more aware of the uses of these materials in displays.

The nematic phase is the liquid crystalline phase most used in display devices. Several different types of displays make use of this phase; some of them have been well developed for commercial devices. The most frequently used and best developed is the TN cell, which has been and still remains the workhorse of the industry. Nearly 50% of nematic materials supplied by Merck-Japan go toward TN displays, and another 10% toward TN active matrix (AM) displays. The latter type is expected to grow substantially in the next 10 years as the TN AM technology dominates the display manufacturing industry in Japan. Currently, the STN is a widely used display for laptop computers and consumes 40% of Merck-Japan nematic materials. Other display types, such as electrically controlled birefringence (ECB) or polymer-dispersed liquid crystals (PDLCs), currently consume only a small percentage of the nematic materials market. PDLC-type displays (Doane, et al., 1982) are the most recent liquid crystal technology and have not yet reached use in a commercial product. An interesting facet of the PDLC technology is its use in switchable windows, which use large quantities of nematic materials and thus could, in the long term, drive down the cost of such materials.

Suppliers and Markets

The Merck group, which consists of E. Merck Darmstadt, Merck-Japan, Ltd., and Merck Ltd., Poole, holds early patents and is a major supplier (50% worldwide) of nematic liquid crystal materials. Their sales breakdown is as follows: 70% to Japan, 25-30% to Southeast Asia, and 1-2% each to Europe and the United States.

The joint venture RODIC claims 30% of the liquid crystal material market in Japan. Hoffman-LaRoche in Basel, Switzerland, supplies Southeast Asia, the United States, and Europe. Other suppliers of nematic materials are listed in Table 2.1. Current costs of nematic materials supplied by E. Merck range between \$2.85 and \$10.00 per gram, depending upon the materials used. This is actually a small percentage of the total cost of an STN or TN AM thin-film transistor (TFT) display. A significant part of these costs results from formulation of mixtures. According to Merck, each sale normally involves mixtures of different liquid crystal compounds prepared to meet the specifications each company wants for its displays. Custom-designed mixtures are code-named to keep a customer's mixture proprietary. It can take as long as a year to get a mixture correct. Merck assumes the responsibility of meeting a manufacturer's specifications. Often the specs are tightened on the next order. Mixtures have involved as many as several hundred compounds. Some customers remix materials or change mixtures supplied by Merck. Purity is always an important issue.

TN and STN Display Materials

Table 2.2 outlines the physical properties of a nematic material that is desired for an STN display, along with values typically provided by manufacturers. These data were graciously supplied by Dr. H. Takatsu of Dainippon Ink and Dr. B. Rieger of Merck-Japan. Table 2.2 clearly illustrates why different STN manufacturers desire different material characteristics: One manufacturer may desire fast response time, whereas another seeks better contrast. Uniformity may be an issue that alters the value of the pretilt used, but not without a compromise in speed. High resistivity, $\sim 10^{12}$ Ωcm , is normally sought for all displays. This parameter is controlled by ionic impurities, hence the demand for highly purified materials. The widest possible temperature range is often desired, and -30 to 80°C is normally achieved and accepted. There can be a sacrifice in temperature range to achieve lower drive voltage in TN displays. Temperature ranges beyond -30 to 100°C are difficult to achieve.

Table 2.3 shows material characteristics desired and achieved for the TN cell on the AM TFT and metal-insulator-metal (MIM) display.

Each company has its own proprietary compounds for mixing to meet desired characteristics. There has been considerable research over the past 20 years in the design and synthesis of low-molecular-weight nematic compounds with improved characteristics, such as lower viscosity, increased temperature range, larger birefringence, and dielectric anisotropy. It is generally believed that further research on the low-molecular-weight compounds will not provide substantial improvements in the nematic physical parameters. Improvements in the STN or TN cells will come primarily from improvements in display design or in other materials used in the

display, such as the alignment layers, which control pretilt and molecular anchoring strengths (discussed later), or retardation films.

For displays with substantially improved features in certain areas such as speed or brightness, display technology generally looks toward other promising kinds of liquid crystal phases, such as the FLC phase, or toward different kinds of materials, such as PDLCS.

Table 2.1
Suppliers of Nematic Liquid Crystal Materials for Displays

E. Merck group -----claims 40% market share

E. Merck, Darmstadt, Germany ---all synthesis at Darmstadt
Merck Poole, England -----focuses on PDLCS materials
Merck-Japan
EM Chemicals, U.S.

RODIC joint venture, Tokyo -----claims 30% Japan market share

Hoffmann-LaRoche, Switzerland --supplier of Southeast Asia
Dainippon Ink, Japan

Chisso, Tokyo

Other Japanese companies

Bohusui
Hoechst, Japan
Kohusai Electric
Mitsubishi Kasei
Mitsui Toatsu Chemicals
Nagase Sangyo
Samco International
Sumitomo Chemical

Table 2.2
Nematic Materials Properties and Display Parameters for STN Displays

Properties and Parameters	for High Contrast	for Fast Response	Typical Values
Elastic constant ratio, K_{33}/K_{11}	large	small	
Dielectric anisotropy, $\Delta\epsilon$	small		
Twist angle	large (220-260°)	small	
Birefringence, Δn			-0.12-0.15
Viscosity		low	~16-23 CSt
Pretilt			5-10°
Resistivity		high	10^{12} Ωcm
Cell spacing			4-7 μm
Threshold voltage			1.2-2V

Table 2.3
Nematic Materials Properties and Display Parameters for a TN Cell

Properties and Parameters	Passive Matrix	Active Matrix TFT	Active Matrix MIM
Elastic constant ratio, K		small	
Dielectric anisotropy, $\Delta\epsilon$	large	large	large
Birefringence, Δn	~0.1-0.16	low ~0.08-0.1	high ~0.15-0.18
Viscosity	~20-30 CSt	~15-23 CSt	~15-23 CSt
Pretilt	~1°	~2-3°	~2-3°
Resistivity	10^{11} Ωcm	10^{13} - 10^{14} Ωcm	10^{13} - 10^{14} Ωcm
Cell spacing	8-10 μm	5-7 μm	5-7 μm
Threshold voltage	0.9-1.8V	1.5-2.0V	1.5-2.0V
Voltage holding ratio		>98%	

FLC Display Materials

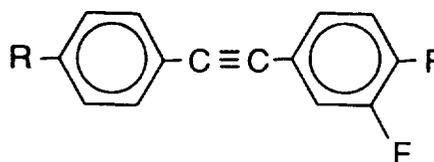
The FLC display offers substantially improved switching times and bistability. The latter feature permits the use of the LCD display for a passive matrix with reduced display cost. A commercial product from this technology has been slow in coming for several reasons: It is difficult to fabricate because of small cell spacing; it is easily destroyed by mechanical shock because molecular anchoring at the surface is unstable; and gray scale is not easily achieved. FLC materials have also not met desired specifications. Although the response time is fast, it is marginal in most materials for line-at-a-time addressing at TV rates on a passive matrix. Mr. Mochizuki of Fujitsu, for example, reports a 120- μ sec response for a 20V drive and 80- μ sec response for a 30V drive; but 30 μ sec is required for addressing 1000 lines at video rates. Higher resolution requires shorter response. A preferred FLC material of Dainippon Ink shows a 60- μ sec response time that could be reduced to 29 μ sec with a sacrifice in contrast. The FLC display recently reported by Canon does not exhibit video rates. Another material problem is temperature range because of the extreme sensitivity of viscosity (and resulting response time) to temperature. There is probably more promise in improving the FLCs with new synthesis and molecular design than there is in nematics for TN and STN, because less has been done. For example, work at Fujitsu and Dainippon Ink showed new materials with a wide smectic A range about the smectic C. Scientists at Fujitsu described how this feature can lead to improved surface stabilization. There is substantial research on FLC compounds in universities and industry around the world. New variations of FLC materials, such as antiferroelectric materials or FLCs from side-chain polymers, do not appear to receive as much enthusiasm from Japanese scientists as from European and U.S. scientists. This is perhaps because scientists in Japan are closer to manufacturers and thus are aware of manufacturing problems. A representative of Fujitsu commented that antiferroelectric materials showed improved stability because of the soft layers, but their contrast ratio was not as good. Possible improvements from other display materials such as alignment layers will be discussed later in this report.

PDLC Display Materials

The area of PDLC materials is a recent technology that has been rapidly picked up, improved upon, and developed for display application by Japanese scientists (Doane, 1991). The physical concepts behind this technology have origins in English patent literature, but materials and processes to bring it about largely began in the United States. The team found that nearly all display companies in Japan had an interest in and maintained a research and development program on these materials. In displays, these materials offer improved brightness because they do not require polarizers and they are relatively simple to fabricate. They are principally interesting for use in projection television, but many companies foresee their use in direct-view displays. Since PDLC materials require the active matrix for

high resolution, most research programs focus on efforts to lower the drive voltage and increase resistivities required for the AM TFT. Two companies have made significant strides in this direction: Asahi Glass reported a full-color video projection prototype using PDLC materials, and Dainippon Ink has developed a PDLC material and is now working with other display companies to develop display products. Both companies show materials that can be used on AM TFT substrates.

There are variations in the amount and type of polymer used in PDLC materials; the amount generally varies from 20% to 70% polymer by weight. Recent materials using gel polymers contain ~2% polymer. Both aqueous and nonaqueous polymers have been used. For high resistivities, both the polymer and liquid crystal material must be of high purity. Hysteresis can be a problem. Nematic materials most desired are those with large $\Delta\epsilon$ and Δn . Dainippon Ink reports the use of fluorinated materials to achieve high-purity nematic materials. An example is the fluorinated tolans, which also exhibit a high Δn :



The characteristics of materials developed by Asahi Glass and Dainippon Ink are shown in Table 2.4.

Although it is still too early to determine all the problem areas in PDLC materials, they include control of hysteresis and polymer chemistry problems. While the use of PDLC technology offers the potential for substantial improvements in the brightness of projection television, there has not been sufficient development time for commercial-grade prototypes to appear.

ECB Display Materials

Materials for ECB LCDs are a very small part of the liquid crystal materials market. Normally, large $\Delta\epsilon$ and Δn materials are desired. Vertically aligned nematics (VANs) require a negative $\Delta\epsilon$.

NCPT Display Materials

Fujitsu plans production of a 5M-pixel black-and-white overhead projection system using a cholesteric nematic phase change (NCPT) display. Under a suitable bias voltage, the material possesses a bistable memory, needing only a passive matrix.

It works on a light-scattering principle, providing for a bright projection display (no polarizers). It has several advantages over the STN projection system: It does not degrade in the center of the picture as the STN has been reported to do; also, according to Fujitsu, its manufacturing cost is lower and high definition is possible. Fujitsu is now developing a 7M-pixel system. Color is possible but not yet fully developed.

A key material to the success of the NCPT is a chiral material that possesses a temperature-independent pitch length over a wide temperature range and a pitch length, p , of $\sim 1.0 \mu\text{m}$ in a cell with an inner electrode spacing, d , of $5\text{-}6 \mu\text{m}$. The memory depends on ratio p/d , which can limit the thickness of the cell and ultimately the contrast of the display. Research efforts underway in the United States are using polymer gel dispersions in the NCPT cell to eliminate this shortcoming.

Table 2.4
Performance Characteristics of Polymer Dispersions
by Asahi Glass and Dainippon Ink for Cells with a
Spacing of $8 \mu\text{m}$ Using a Light Collection Angle of 8°

	<u>Dainippon Ink</u>	<u>Asahi Glass</u>
Driving voltage	4 ~ 8V	6 - 7V
T_0	2 ~ 5%	
T_{100}	80 ~ 83%	
Contrast		100:1
$t_{\text{ON}} (V=V_{90})$	2 ~ 10 msec	
$t_{\text{OFF}} (V=V_{90})$	10 ~ 20 msec	
Resistivity	$5 \times 10^{10} \sim 2 \times 10^{11} \Omega\text{cm}$	$5 \times 10^{10} \Omega\text{cm}$

University LC Materials Research in Japan

There is considerable research in Japan aimed at developing new types of liquid crystal materials and displays with improved features. This research is conducted in both industry and universities, but the more basic work is being done at universities. The team visited and interviewed two leading professors in Japan involved in display materials, Professor S. Kobayashi of Tokyo University of Agriculture and Technology and Professor T. Uchida of Tohoku University. Professor Kobayashi outlined the fundamental issues important in a display (Table 2.5). In Dr. Kobayashi's view, no technology can cover all of these issues well; but he claims that all liquid crystal technologies can cover these issues sufficiently well and if pursued strongly enough could become marketable technologies. Therefore, he said, all LCD technologies should be explored.

Professor Kobayashi pointed out the need to develop a direct-view display without a backlight. In none of the companies the JTEC team visited in Japan were there any discussions on this topic. However, Professor Uchida showed an interest in reflective color displays; he has achieved a reflectivity of about 20% and a contrast of 5:1 using a dichroic dye guest-host type display.

Table 2.5
Basic Issues Important for a Display of Commercial Value

1. Information content (resolution)
2. Viewability
 - a. Legibility (contrast ratio and luminescence)
 - b. Full color capability
 - c. Gray scale
 - d. View angle
3. Cost of driving circuits
4. Production costs (yield, throughput)
5. Space (flat-panel, weight)

Often trade-offs between 1 and 2; 1,2 and 3,4

Professor Uchida estimated that about 100 physics and 100 chemistry faculty members in Japanese universities are working on materials and chemical physics problems related to displays. Few are actually developing a display. Table 2.6 lists areas of interest in Japan mentioned by Professors Kobayashi and Uchida.

Table 2.6
Areas of Research Interest in Japanese Universities

Ferroelectric Liquid Crystals

Bistability
Gray scale

Surface Alignment Materials and Problems

Langmuir-Blodgett films
Polar anchoring
Torsional anchoring
Conductive orientation films

Retardation Films

Impurity Films

Polymer Dispersions, PDLCs

Electroclinic Effects

S_A - S_C phase transition

The funding for university research in Japan comes primarily through the Ministry of Education (MOE) through such agencies as Japan Society for the Promotion of Science (JSPS). Each agency has many committees in areas such as materials science, laser technology, and so forth. These committees are supported in part by the government and in part by industry. Professor Kobayashi maintains an effective grant on "Cooperative Research with Incorporated Organizations" through MOE. In this grant effort Dr. Kobayashi has projects with five companies on FLCs, AM LCDs, High Definition (HD) LCDs, LC alignment layers, and flexible displays.

OTHER LCD MATERIALS

Many materials besides the liquid crystal are important to the operation of an LCD. As display technology advances, the role of these materials becomes more important. Some of the important materials are discussed below.

Alignment Layer

In every LCD the LC material must be anchored in some way to a surface associated with the display. In the case of a TN, STN, ECB, or FLC, the surface is the glass substrate. In the case of a PDLC, the surface is the droplet wall of the polymer. There are various ways the elongated liquid crystal molecule can be anchored to a wall: perpendicular, parallel, or at some angle (often called a pretilt). The strength of the anchoring is important, because it must compete favorably with the elastic energies of the liquid crystal in the presence and absence of applied fields.

Very little is known about surface anchoring, and it is usually treated as "black magic" with standards and techniques. Industry currently prefers the polyimides for the alignment layer. Each industry has its own proprietary way of preparing layers. Scientists at Merck-Japan say that customers for materials usually request nematic mixtures based on their own proprietary alignment layer. Some customers seek advice, and Merck-Japan and Dainippon Ink are doing some work on how their materials respond on various surface layers. At Dainippon Ink, an R&D program is working on controlling pretilt by mixing polyimide derivatives that give low pretilt with other derivatives that provide 90° anchoring to give a desired tilt angle.

The stability of high pretilt in the STN display is a problem, particularly for uniformity. There is research in Japan, such as at Dainippon Ink, not only to improve or strengthen high pretilt anchoring but also to better understand the anchoring mechanism. The subject presents several problems, some of which Professor Kobayashi's laboratory and Tokyo University is working on (see Table 2.6). Innovative work there uses Langmuir-Blodgett films to avoid rubbing and conductive alignment layers to solve "second-order" cross-talk or ghosting from charge buildup. Theoretical and experimental programs are studying the polar and torsional components of anchoring.

Japanese suppliers of alignment materials include Nisshin Chemical, Japan Synthetic Rubber, Hitachi Chemical, Toray, and others.

Retardation Film

Retardation film is a Japanese innovation to improve contrast on STN and TN cells and to provide for black and white and color on STN display cells. The principal

operation of the film is to retard or shift one component of the light to convert the elliptically polarized light generated by the display cell into the linear polarized light required by the polarizing sheet, as Figure 2.1 illustrates. The film is sometimes referred to as a *phase compensating sheet* or *compensator*.

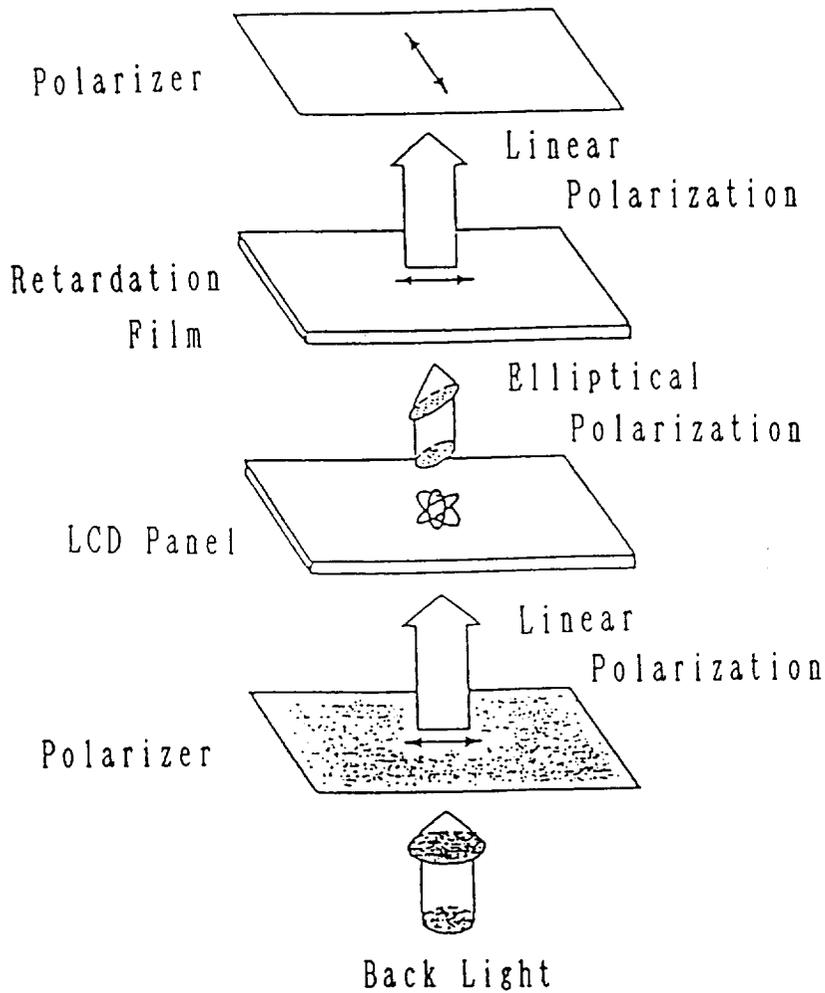


Figure 2.1. Illustration of a Retardation Film
(Courtesy of Nitto Denko)

An important feature of the retardation film is that it offers uniform retardation over the wavelength spread of the visible spectrum. Nitto Denko has performed research in this area using different polymeric materials and polymer film combinations (Kato et al., 1991).

Another interesting feature studied and reported by Nitto Denko is the use of retardation films to enhance the viewing angle of a TN or STN display. They have shown the importance of controlling the refraction index of the film in three directions, n_x , n_y , and n_z . Figure 2.2 shows one of their plots, illustrating how the proper selection of indices can give the retardation a desired angular dependence by proper selection of indices.

Retardation film suppliers include Nitto Denko, Sumitomo Chemical Inc., San Ritz Corporation, Toray, Kayapolar, and others.

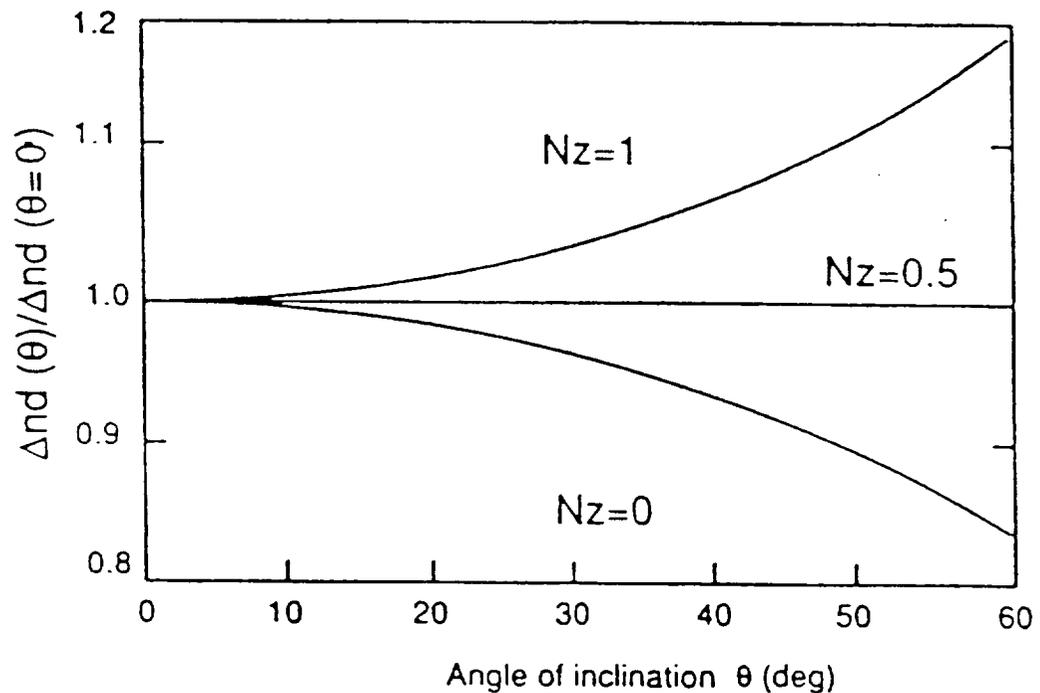


Figure 2.2. Illustration of the Change of Retardation Versus View Angle Control by Adjustment of the Three-Dimensional Refractive Index

Color Filters

There are a variety of ways of making RGB color filters for full-color active and passive matrix displays. Four preferred methods are illustrated in Figure 2.3. Toppan Printing indicated a fifth, dichroic, method. For LCDs the dyeing type has been the predominant method, according to Toppan, but pigment-dispersed filters are expanding because when compared with the dye method they prove to be superior in light resistance for TV, automobile, and aircraft applications.

The cost of production is equally high for dye-method and pigment-dispersed filters. The pigment-dispersed filter is spun onto the substrate: an easier method of production than used for the dyeing type. Fuji-Hunt is the top vendor of pigment-based filter materials. Roller coating could reduce the amount of pigment-dispersed filter material. Low-reflectivity chrome is used for the black matrix, and it is patterned with a stepper. An overcoat is deposited on the gelatin filters (but not often for pigment filters) before the indium tin oxide (ITO) is deposited. Improvement in light transmission through pigment-dispersed filters is under investigation. If the pigment is made smaller, transmission increases, but generally speaking the light resistance has a tendency to gradually decrease.

Method name	Description	Features		
		Resolution	Color reproduction	Reliability
<p>Gelatin dyeing method Patterned resin is dyed.</p>		○	○	△
<p>Pigment impregnation method Resin containing pigment is made into a pattern.</p>		○	○	○
<p>Printing method Color ink containing pigment is printed on.</p>		×	△	○
<p>Electroplating method A resin coat is electroplated on the pigment surface</p>		△	○	○

Figure 2.3. Color Filter Formation Methods
(Courtesy of Sharp Corporation)

Companies have investigated producing color filters by electrodeposition, but this method can be used only with certain filter layouts (such as stripe) in which there is a continuous path from one side of the display to the other. Printing technologies offer the possibility of fabricating low-cost filters. According to Toppan, the main issue with printing is the maximum size of substrate. A comparison of the dye, printing, and pigment methods is shown in Table 2.7, supplied by Toppan.

Table 2.7
Characteristics of Color Filters
(Information supplied by Toppan)

TYPE	DYEING	PIGMENT DISPERSED	ELECTRO- DEPOSITING	PRINTING
THICKNESS (μM)	1.0 ~ 2.5	1.0 ~ 2.5	1.5 ~ 2.5	2.0 ~ 3.5
COLOR	⊙	○	○	○
RESOLUTION (μM)	10~20	10~20	10~20	70~100
SURFACE	○	○	○	△
HEAT ($^{\circ}\text{C}/\text{hour}$)	180	260	250	250
LIGHT (HR) (Xe Lamp 1000001x)	100	>500	>500	>500
CHEMICALS	△	○	○	○
BINDER	gelatin	acryl	acryl- epoxy	epoxy
COLORANT	dye	pigment	pigment	pigment

Color filter suppliers include Toppan Printing, Dainippon Printing, Fuji-Hunt Electronics, Hoya, Kyodo Printing, Nagase Sangyo, Nippon Sheet Glass, RODIC Shinto Chemitron Co., and Toray.

Glass Substrate

Major components of the display are the flat-glass substrates, which must meet demanding specifications that are challenging to today's glass manufacturers. The glass must incorporate a high degree of flatness over large areas as well as a high level of microscopic-scale flatness for low-temperature processing for TFT manufacturing. For AM displays the most popular glass is a borosilicate glass that Corning produces using a fusion draw process. Corning's 7059 glass has a strain-point temperature of 590°C and has about 90% of the AM market. Japanese companies such as Nippon Electric Glass (NEG) and Asahi Glass are developing competitive technologies. NEG produces an alkali-free sheet, OA-2, and is attempting to increase its market share by specifying OA-2 with a slightly higher strain-point temperature of 635°C and fewer defects. A recent price increase by Corning is expected to help NEG, which has sufficient manufacturing capacity to supply a greater market share. Asahi Glass is also working on a high-temperature flat glass, but its researchers are not attempting a strain-point temperature greater than 600°C because they believe lower temperature polysilicon processes will be developed. Asahi Glass claims its product improves on Corning's 7059 in flatness and etch resistance. A concern over a stable supply of glass for TFT LCDs was expressed during the visit to Asahi Glass. Where high-temperature processing is not required, as for technologies on a passive matrix, the lower cost conventional soda-lime glass can be used if a passivation layer is added to one surface to provide a barrier for ion migration. Companies such as Pilington Micronics in the United Kingdom continue development of lower cost soda-lime substrates. There is hope that in the near future TFT processes will allow use of these substrates, which can be made on high-quality float lines.

Polarizing Sheets

The area of polarizing sheets is a more mature technology, with several suppliers in Japan. Typical properties quoted for the optical properties of these films include a transmittance of 40-43%, with a degree of polarization closely approaching 100%. Concerns are the deterioration of the transmission and of the polarizing efficiency. Mr. Mochizuki of Fujitsu mentioned that problems with the polarizer can become apparent when STN displays are used on overhead projectors. With time the image loses its uniformity, an effect that is thought to be primarily due to bleaching of the polarizing sheets.

The charts (Figure 2.4) for a polarizing film under development by Toray can give an estimate of state-of-the-art film stability. Figure 2.4 is a reproduction of Toray's announcement for a HC type (high polarizing efficiency/high durability type) under a test condition: 60 deg., 90 RH.

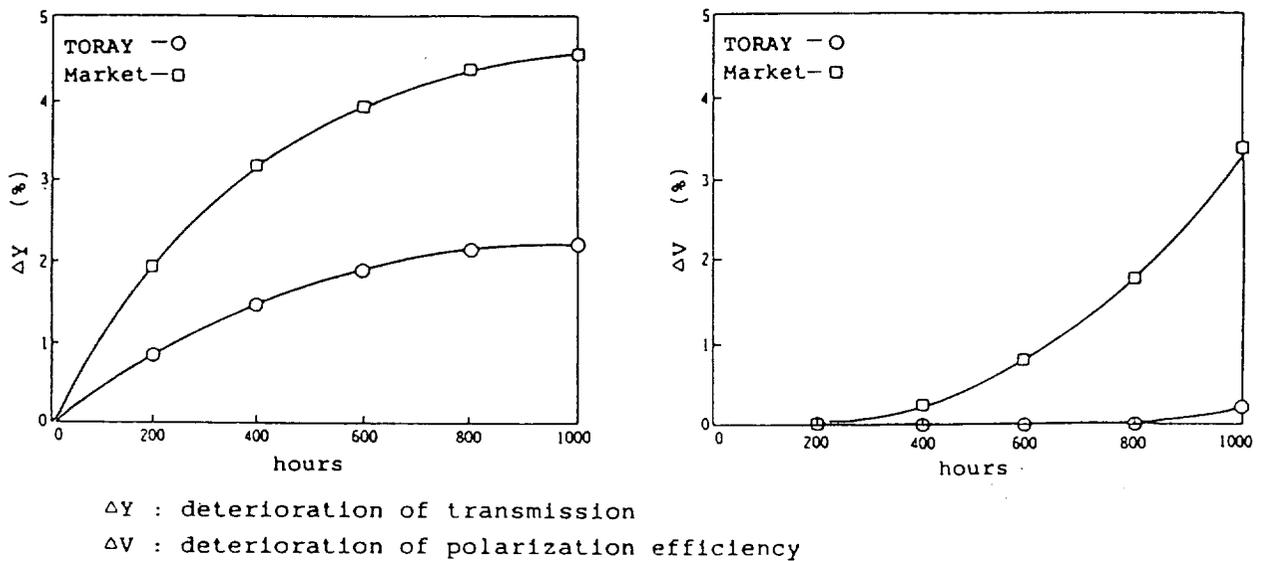


Figure 2.4. Stability of a Polarizing Film Under Development
(Courtesy of Toray)

Spacers

A useful product that is available only through Japanese suppliers is precision plastic spheres ranging from 3 to 4 μm in diameter. These spheres are particularly useful as spacers where soft (plastic) substrates are used, say for PDLC displays. One supplier of this product, under the name of micropearl SP, is Sehisai Fine Chemical Co., Ltd., in Osaka-shi.

LIGHT-EMISSIVE DISPLAY MATERIALS

Because of Japan's large investment in LCDs and because of the expertise of the review team members, the team placed heavy emphasis on reviewing LCD technology; however, it did make some observations on materials development in electroluminescent (EL) and plasma display panels (PDP). Because these technologies have the potential to achieve full color, Japan has dedicated research efforts on materials for them. It is argued that current LCD technologies require backlights with driving power approaching that of EL and PDP; thus, these technologies are potentially competitive with advanced materials and better cell design and fabrication methods (Pleshko, 1991; Friedman, 1991).

EL Materials

An excellent overview of material development in Japan was provided by Professors H. Kobayashi and S. Tanaka of Tottori University, who have worked with a number of companies: Sharp, HEC Kansai, Ohi, Fuji Electric, Nippon Sheet Glass, Matsushita, Komatou, and Tosio. In their opinion, the brightness of a blue phosphor must be improved by a factor of five or six before the EL technology can become viable. They believe that EL could support 1000 x 1000 pixels without serious cross-talk problems. Cross-talk minimization and gray scale are both areas that need work.

A DC EL power/thin-film hybrid display is being studied by Nippon Sheet Glass, which has a 640- x 480-pixel display with 16 levels of gray with pulse width modulation. Materials work at Tottori is focused on improving the performance of color, particularly blue and white phosphors, by incorporating lithium, potassium, and sodium as charge compensating materials. The following phosphor combinations are presently under study in the Tottori University laboratories:

Red, CaS: Eu
Green, ZnS: Tb,F
Blue, SrS: Ce,K
White, SrS: Ce,K,Eu and SrS: Pr,K

Tottori researchers report reasonable progress in both blue and white phosphors, especially when using an ArS atmosphere anneal at 630°C. They have shown three colors using their white phosphor with both dye and interference filters, with the dye filters providing a larger viewing angle. There appear to be trade-offs between this way of achieving color and that from RGB phosphors.

The EL technology is a difficult technology, and commercialization is not easy in Japan because EL has lower status than other technologies. Thus, researchers at

Tottori University chose to publish their results rather than patent discoveries, to encourage more interest from Japanese industries.

PDP Materials

In recent years there have been substantial advances in the design of the discharge cell structure to prevent phosphor degradation from ion bombardment, giving encouragement for full-color PDP displays. With these advances, color PDP does not appear to be material-limited, although improved discharge gas and electrode materials would be welcome. Using phosphors requires gases that are efficient UV emitters but are not visible light that can compete with light from excited phosphors. Coatings that protect phosphors and that do not strongly absorb in the UV are needed (Friedman, 1991). Studies of phosphor excitation are also needed to improve the efficiency of phosphors (Komatsu, 1991).

The team did not have the opportunity to visit Japanese laboratories working on PDP materials. Hiroshima University and Photonics Imaging have recently made color AC-PDPs, and a color PDP was demonstrated at the 1991 Japan Electronics Show.

CONCLUSIONS

TN, STN, and ECB Materials

Low-molecular-weight nematic liquid crystalline materials for TN, STN, and ECB displays are well developed, and substantial improvements in such features as reduced viscosity, enhanced dielectric anisotropy, and birefringence are not expected. Major European nematic materials producers have established joint ventures in Japan to tailor-make mixtures for display manufacturers. Japanese companies are taking an increasing role in designing, synthesizing, and patenting new nematic materials, while European companies are protecting their strength by keeping their research and development efforts at home and only making mixtures in their joint ventures in Japan.

Most improvements in the TN and STN displays are expected to come from other materials such as retardation films and improved alignment layers. Retardation films are a Japanese innovation, and Japanese companies are currently the only suppliers of such films. There is room for substantial improvement in retardation films. Alignment layers that do not require rubbing would be welcome in the industry. Innovative materials and techniques for molecular surface alignment are primarily being explored in Japanese universities such as the laboratory of Professor S. Kobayashi, who is working on Langmuir-Blodgett films and conducting polymers.

FLC Display Materials

Improvements are expected to come from the synthesis and design of new low-molecular-weight LC materials for FLC displays, and several Japanese companies are studying new molecular forms. Discussion with several companies did not indicate as much enthusiasm in Japan as in Europe for new antiferroelectric LC materials. There did not appear to be any new solutions to the surface stabilization problem, other than that mentioned by Fujitsu, which has been approaching the problem by designing FLC materials that stimulate the bookshelf-ordering structure. Gray scale was perceived to be a major problem by most of the Japanese companies the JTEC team visited.

PDLC Materials

Most Japanese display companies visited had research programs on PDLC materials, and there appeared to be wide interest in these materials for projection applications. Some companies also viewed these materials as having potential for brighter direct-view displays. Drive voltage and resistivity problems in the use of these materials on the active matrix are reported to be nearing solution. Asahi Glass and Dainippon Ink show PDLC materials with impressive characteristics. Improvements in the polymer binder and in the nematic materials used in the dispersions are responsible for these advances.

EL and PDP Materials

Research on materials for light-emissive displays is perceived to be de-emphasized in Japan because of the strong commitment to LCD manufacturing. Advances are being made in the development of blue and white EL phosphors. In PDP displays, new designs and success in discharge cell structure are expected to give new focus to materials research.

University Materials Research

University researchers in Japan are more aware of display materials problems and industrial needs than are their counterparts in the United States and Europe. University research is more basic in general, and approaches to industrial problems more innovative. In Japan, basic research on liquid crystals is more driven by the display technology than in the United States and Europe. There are joint industry/government research support programs that encourage university/industry interactions.

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CHAPTER 3

MANUFACTURING AND INFRASTRUCTURE OF ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS

Malcolm Thompson

INTRODUCTION

Over the past few years, an impressive array of active matrix liquid crystal display (AMLCD) products have been developed that demonstrate very high-quality display performance. There is intense interest in and demand for such displays for computer, avionic, automobile, and consumer products. The growth of the AMLCD market will be controlled by manufacturing capacity and cost. In the second part of the 1980s, many Japanese companies (display manufacturers and materials and equipment suppliers) made plans for large financial commitments to this technology. Now, in the early 1990s, very large manufacturing facilities are being built to meet the enormous demand for AMLCDs. The initial largest product volume is in color video graphic adapter (VGA) displays for the laptop computer market. With known committed investments of over \$2 billion, there is considerable pressure to quickly achieve high manufacturing yield and low cost and obtain an acceptable return on investment. Manufacturing issues have become the prime focus of research and development. There is intense competition for market share, because many major Japanese corporations view this area as a strategic long-term investment.

AMLCD manufacturing technology is unique, but it has some similarities to integrated circuit (IC) and conventional LCD processes. Although all the major research discoveries in LCD materials and applications were made in Europe and the United States, Japan has dominated the world production of twisted nematic and supertwist displays. Many of the techniques used in cell assembly in these technologies are similar to those used in AMLCD. The dominant active matrix technology is thin-film transistors (TFTs) of either a-Si or p-Si. The lower process

temperature (<400°C) of a-Si has led to its initial dominance in large-area AMLCD technology. There is in Japan substantial experience and infrastructure in large-area a-Si manufacturing for solar cells, which was initiated by the Ministry of International Trade and Industry (MITI) during the oil crisis of the 1970s. Some of this experience, in particular large-area a-Si deposition, has been useful, because there are now in Japan established suppliers of large-area plasma-enhanced CVD (PECVD) manufacturing equipment. The present manufacturing of p-Si LCD displays is confined to small-size quality substrates (<6 inches) using high-temperature "IC-like" processes. Most of these products are for small high-density camcorder and projection applications. Low-temperature large-area p-Si device and process development are still in the research stage in Japan. While there is considerable interest in developing low-temperature p-Si AMLCDs because it would be possible to incorporate p-Si built-in drivers in the display, most Japanese companies have had to devote their resources to making the manufacturing of a-Si AMLCDs successful.

There are a considerable number of publications that describe device architectures and display performance, but manufacturing processes and yield issues naturally remain as company secrets in this intensely competitive market. This chapter describes some of the a-Si AMLCD factory logistics and discusses some aspects of throughput yield and defects that have been deduced from many visits and discussions with a considerable number of manufacturers. Some major manufacturing equipment is described, along with a number of other infrastructure issues. Given some of the sensitive issues surrounding manufacturing of AMLCDs, precise information is not directly available; thus, some of our information is based on incomplete data.

MANUFACTURING LOGISTICS

Most of the AMLCDs are manufactured at the sites of existing facilities where electronic components, ICs, and LCDs are already produced. Thus, an existing infrastructure and experienced manufacturing organizations are available to initiate and support new and complex facilities. The initial AMLCDs were manufactured in modified IC clean room facilities. During 1991 a number of new, large facilities were constructed at existing manufacturing sites such as Tenri (Sharp) and Himeji (Toshiba/IBM Japan - DTI). The new investment at these locations is \$200-400 million. Because of the limited availability of land, multistory clean rooms have been built, with elevator transport of substrates between floors.

A summary of some 10-inch color TFT/LCD VGA production lines is shown in Table 3.1. The total investment and sales goals are shown in Table 3.2.

Table 3.1
Some 10-inch Color TFT Production Lines

Supplier	Site	Operation start	Panel size (inches)	Capacity (in 10-inch)	Investment	Function of site	Remarks
Sharp	Tenri	1986	3-6	unknown	¥14b for 2nd 6-10 inch line 1989;	3-6 inch production, 10-inch dev.	10-inch capacity 3000-5000/year
	Tenri-new	4/91	6-10	5 times previous (1st phase)	phase 1 ¥27b, phase 2 in F1991-1992	10-inch production until 1993	1st investment in F1990, 2nd and 3rd investments F1991-F1992
	Mie	8/93	over 10	unknown	phase 1 ¥40b	main plant after 1993, ¥50b production in first year	also 14-inch production, construction starts July 1992
DTI	DTI	4/91	at least 10	42,000/month (1st phase)	¥39b (phase 1) ¥15b (phase 2)	main plant until 1995	prototype development line at Toshiba Taishi plant began 12/89
Hitachi	Mobara-new Mobara-old	10/88 undecided	5, 10 10, 12.5	10,000/month unknown	¥10b (for equipment) undecided	small lot and prototype main plant by 1995	1000/month production began summer 1990
Hosiden	Dev. Tech. Research Lab.	10/87	3-10	60,000/month	¥15b (phase 1)	main TFT plant	prototype of 4 panels per sheet
NEC	Tamagawa Kagoshima NEC	mid 1985 8/90	4.3-9.3 4.3-9.3	2000/month 20,000/month (1st phase)	¥5-6b (cumulative) ¥10b (phase 1), using existing building	TFT dev. prototype line	making PCs with TFT panels
						main plant by 1995	began investment 8/90, begin output late 1990
Matsushita Electric	Ishikawa	3/91	10-inch	5000/month	¥40b (phase 1), of which ¥15b for construction	TFT dev. & prototype, STN mass production	equipment investment ¥25b, 60% for large TFT

Source: Nikkei BP

Table 3.2
Sales and Investment Plans of LCD Suppliers

	1989	1990	1991	1992	1993	1994	1995	
Sharp ★	¥14Bil. 45	← Totally ¥100B →		67	115	165	← Totally ¥100B → 500	
Seiko Epson	10 45	10 60	10 75	10 100	← Not Decided → 1300			
Optrex	2.5 28.4	10 36	5 42					
Hitachi ★	10(Mobara) 22	← Not Opened →					30	40
Toshiba (incl. DTI) ★	n/a 20	32 26	after fiscal 1991, total of 80 over 4 years				50	> 100
Tottori Sanyo Elec.	50 20	15 26	← Totally ¥450B →		33	100		
Casio Computer	0 14	55 20	130 30	← 380 →		40	50	
Matsushita Electric	n/a 12-13	← Totally 40 →		18-20	← Not Decided →		50	
Stanley Electric	5 12	4~5						
Hosiden	5 11.5	0.5 12	5 14.5	6.5 17.5	7 21	25	70	
Seiko Instruments	several bil. 10	several billion every year after 1990						
Alps Electric	n/a	10	15	20	24~2 5			
Citizen Watch	7	color STN, small hi resolution panels					13	15
NEC ★	2 0	8	8	← 60 →		17~18	25	
Mitsubishi Electric	n/a --	n/a --	20	15-20 % of TFT Mkt				
Fujitsu	n/a --	several bil. substantial increase		20<				

★ = Major Investment

Manufacturing Process

Most manufacturers use very similar TFT and LCD fabrication processes. An example of the TFT process is summarized in Figure 3.1. A possible variation of this process is to replace the top SiN deposition by a N+a-Si deposition (SiN/a-Si/n+a-Si). This necessitates the use of a very thick a-Si layer because there is no etch stop for the n+ etch on the intrinsic a-Si. Both wet etching and dry etching are used to pattern the thick film layers. Some companies use precoated ITO substrates; thus, the first step is to pattern and etch the layer. Careful inspection of substrates is absolutely necessary, given the immaturity of the manufacturing process. The precise process monitoring procedures are not revealed, but most inspection techniques are optical and electrical.

The liquid crystal process, while not devoid of problems and yield issues, is much more mature because of its similarity to supertwisted nematic (STN) production process tools. Process optimization to provide good viewing angle and uniformity is significantly different for AMLCDs, but the equipment and production techniques are similar. The cover-plate color-filter process is extremely important; it can be a very expensive process because of high materials cost and low yield. Various processes can be used to fabricate color filters. Dye and pigment filters are most commonly used, as described in Chapter 2. At the moment, most AMLCD manufacturers buy cover filter plates from an outside vendor such as Toppan Printing or Dai Nippon Printing.

Clean Room Layout

Large custom buildings have been constructed, with each floor 4000-6000 square meters and with 1800-5000 square meters of clean room space per floor.

Schematic layouts of three of the new clean room facilities are shown in Figures 3.2, 3.3, and 3.4. The LCD process equipment was often arranged ergonomically in a process flow sequence, whereas in the TFT line the equipment was often arranged in a clustered area of photolith and wet etching, CVD, sputtering, and dry etch. The lack of complete in-line process flow layouts reflects the immaturity of the process. The cluster areas allow for flexibility of process maturing. The lithography areas with wet etch are commonly Class 10. Much of the area is Class 100 for sputter and CVD loading, with the rest Class 1000-5000. The large PECVD and sputtering machines are mostly situated outside the clean room, with the loading and unloading stations inside the clean room.

It is expected that when all floors are utilized, some of these facilities will be capable of producing 1 million VGA displays per year in 10,000-16,000 square meters of clean room.

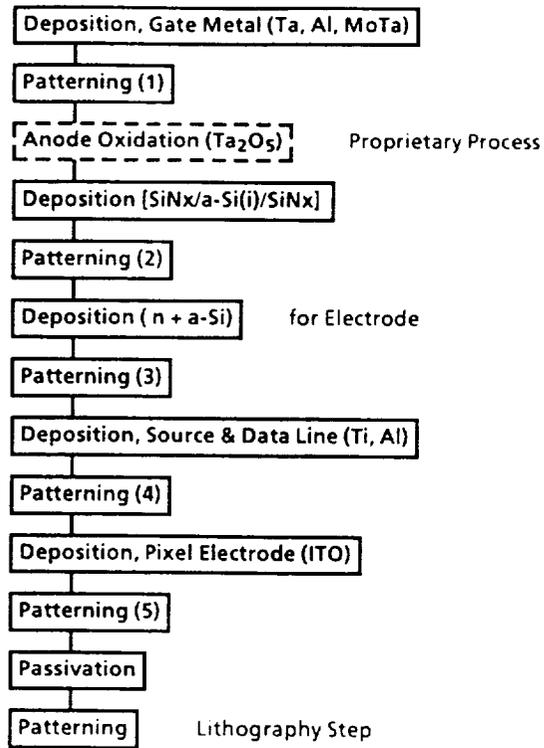


Figure 3.1. Process for a-Si TFT Array

LIQUID CRYSTAL PROCESS			
SPUTTER	CLASS 10		
CLASS 100	RESIST COAT	EXPOSURE	DEVELOPERS
CVD	CLEAN	CLASS 5000	ETCH

Figure 3.2. Process Layout

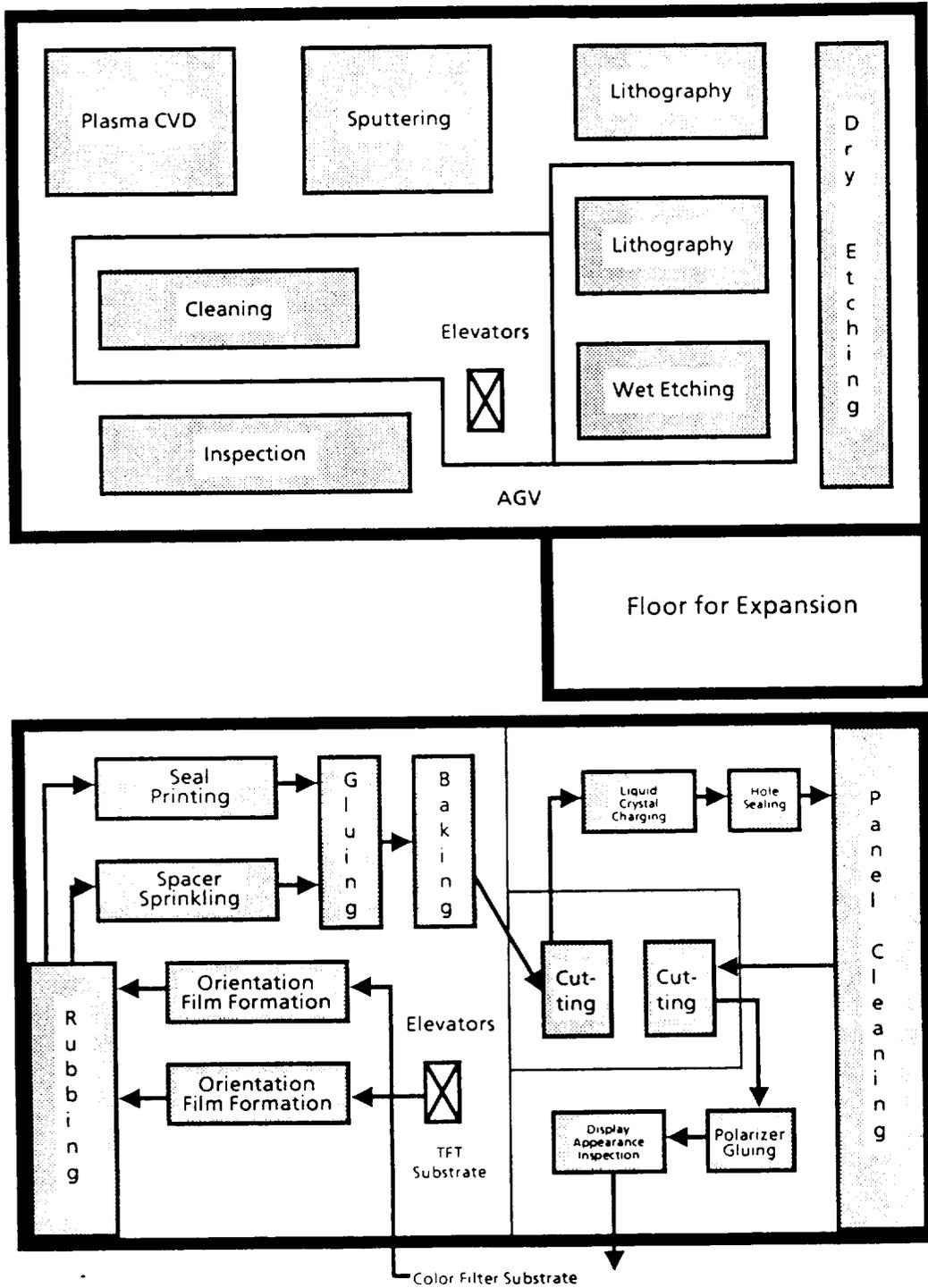


Figure 3.3. Plant Layout

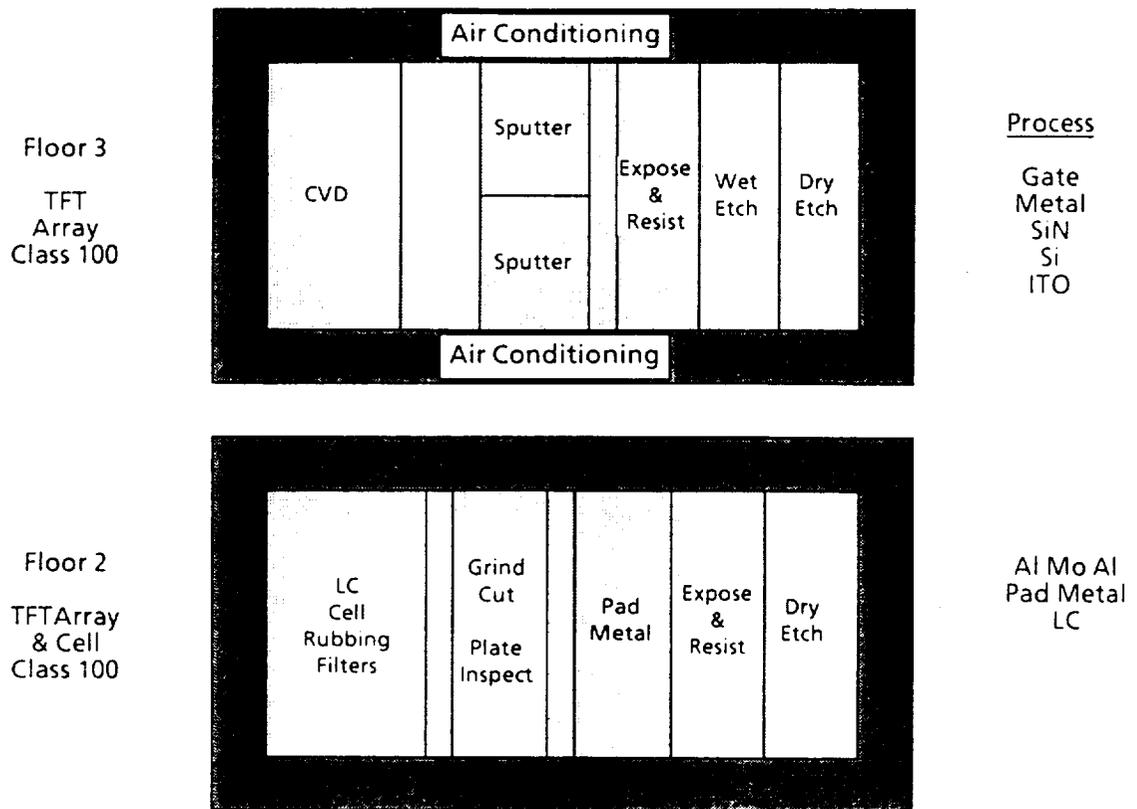


Figure 3.4. Plant Layout

In these production lines the JTEC committee saw 4-12 steppers with 4-6 large PECVDs and large numbers of dry etch machines, indicating their low throughput.

At the initial level of operation of 20,000-40,000 VGAs per month, there will be 70-120 operators and engineers per shift, with a three-shift-per-day operation. From 50% to 60% of these people will work on the TFT line, with the rest equally distributed between LCD process and assembly. The cycle times are as follows:

- o 15-21 days for TFT
- o 3-7 days for cell assembly
- o 7 days for module assembly and test

This implies that 20,000-30,000 substrates will reside in the TFT line at any one time, presenting a major storage and logistics problem. Many of the engineers have had IC photo-semiconductor or LCD production experience.

Transportation and Automation

The substrates used in the new facilities are Corning 7059; in size they range between 300 x 400 mm and 350 x 450 mm. The substrates are transported and stored in cassettes that hold approximately 25 substrates. How the substrates are transported between equipment varies from one facility to another:

- o hand-carried
- o open cassette on automated guided vehicle (AGV)
- o closed cassette on AGV with Hepa filter and fan

With the AGV systems, substrates are often transferred by robots to a station close to the process equipment. Often the substrates are loaded manually onto noncassette equipment such as CVD and sputtering units. Automated robotic loading is being evaluated for this purpose but is not yet functioning satisfactorily.

Throughput Yield

Given the high cost of capital equipment, high yield and throughput must be achieved to achieve low manufacturing cost.

The throughput is strongly influenced by processing time and equipment downtime for cleaning and maintenance. Lithography and, in particular, PECVD are the most critical areas in which equipment limits throughput of AMLCD manufacturing facilities. Because there are many (6-10) masks in the process, lithography is critical and strongly influences productivity. Resist deposition by spinning has a throughput of around 1 substrate per minute. Lithography stepper throughput is dependent on the number of reticles used for the exposure. For symmetric repetitive patterns, a single mask can be stepped across the substrate to expose the layer pattern by stitching together exposures. For nonrepetitive patterns, such as the final metalization, multiple reticles must be used to expose the entire substrate. Reticule change time significantly decreases throughput, which can be greater than 1 minute per substrate for multiple reticles.

The most critical issues of throughput and yield are in the PECVD process. Up to eight substrates are processed in a batch, with a minimum tact time of 10 minutes in an Anelva multichamber system. The tact time consists of substrate transfer time between chambers and heating and deposition time. However, the biggest issue with PECVD is the relatively long downtime needed for equipment cleaning. In production, cleaning may be needed after 3-15 days of operation. Cleaning is extremely important to achieve high yield through maintaining low levels of particulate. The deposition chambers have to be cooled to room temperature to be mechanically cleaned. Plasma etching of the stainless steel chambers at the

deposition temperatures of 250-350°C is not possible because the stainless steel is attacked, producing carbon deposit and generating additional particles.

Considerable improvement is also required in dry etching throughput.

Yield still remains the most critical and elusive challenge in manufacturing AMLCDs. Given the confidential nature of the subject, there is little precise information on manufacturing yield. There have recently been reports that a few companies are achieving >50% yield in manufacturing VGA displays. There is no way of substantiating this information, but it is clear that all the major display manufacturers are putting considerable emphasis on improving yield of AMLCDs. It also should be noted that the volume of AMLCD VGA displays produced in 1991 was considerably less than some forecasts had predicted.

Some of the major issues in achieving high yields are as follows:

1. Particulates generated in PECVD and sputtering. The deposition of a-Si and Si₃N₄ by PECVD produces particulate in the plasma and causes flaking of deposited thin films from areas of the chamber. Special precautions are taken, such as using slow initial pumping speed to avoid disturbing particles on the chamber walls. Particles generated from film flaking present similar problems in the metal sputtering systems.

Particles generated in CVD and sputtering cause interlevel shorts and shorts between adjacent metal lines. They can also cause opens when they fall off, or are removed from the substrate.

2. Electrostatic charging, which causes large TFT threshold shifts and dielectric breakdowns, provides a difficult challenge unique to this transistor technology because the glass substrate is electrically insulating. As the substrates are transported inside equipment and around the clean room, friction and movement between the substrate and electrically insulating transport belts and rollers can generate extremely high voltages on the substrate. Equipment vendors have paid considerable attention to this issue, using electrically conducting parts touching the substrate and in certain cases incorporating ionizers in substrate loading and unloading stations. Shorting bars are connected to the data and scan lines around the periphery of the display and are cut after processing.
3. Sudden changes of particle levels have been reported due to glass chipping or breaking and other issues. Substrate handling and transportation continue to be improved.

4. There are several reports that achieving high yield in the LCD process is as challenging as in the TFT process. This is a major problem because the substrate has high cost value by the time it reaches the LCD process. Particle control at this part of the process is critical to maintaining good cell uniformity and yield.

Tables 3.3 and 3.4 show the distribution of defects in the AMLCD process. In the TFT process a defect associated with the metal X and Y address lines is the biggest issue. This is not surprising, considering that a 10-inch VGA display has over 30 meters of metal interconnect.

Particles easily stick to the glass substrate because they often have some finite residual electrostatic charge, even in the best circumstances.

Innovative testing, in-situ monitoring procedures, and improved manufacturing equipment and practices will provide significant increases in AMLCD yield. Finally, substrate cleaning techniques and substrate handling systems require further improvement.

Table 3.3
Causes of Defects in TFT LCD Manufacturing

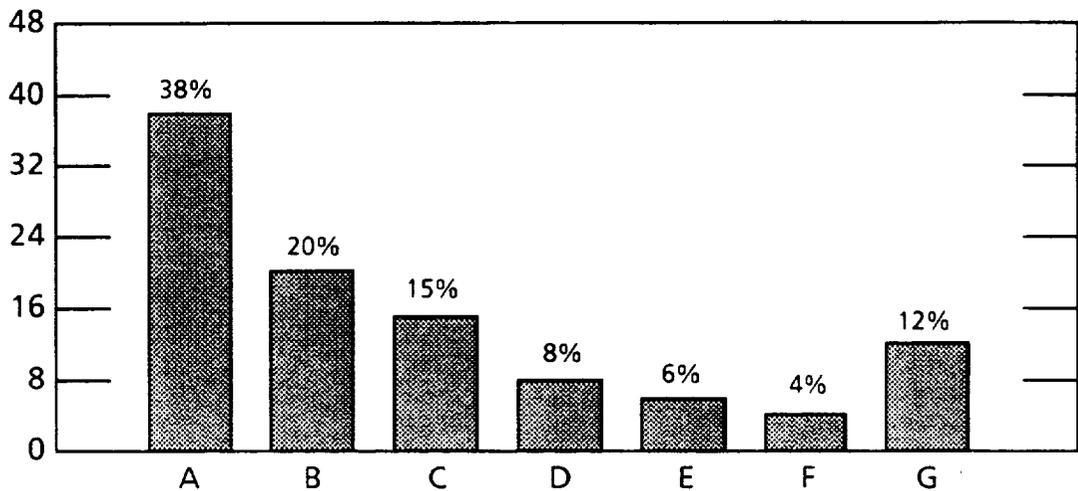
Composition		%	Composition		%
Array Process	Severed Signal Line	26.1	Cell Process	Point Defect*	32.6
	Breakage	24.8		Dust, Scratches, Dirt*	24.7
	Mo-Ta Etching Remnant* .	23.0		Breakage	4.9
	Faulty Characteristics	11.2		Line Defect*	7.7
	Other	14.9		Faulty Gap*	6.1
				Other (i. e., unevenness)* .	20.4

Source: Nikkei BP

* Indicates that dust is a factor. One half of the array defects and 90% of the cell process defects are linked to dust.

Table 3.4
Correlation and Distribution of Defects

	<u>Particles</u>	<u>Organic</u>	<u>Inorganic</u>	<u>Surface</u>
Short Circuit (Same Plane)	S			
Short Circuit (Interlayer)	S	M		M
Open Circuit	S	S		S
Nonuniformity	M	S	S	
Point Defect	S	M	M	M
	S = Strong		M = Medium	



A = Planar Short Circuit; B = Interlevel Short Circuit; C = Open Circuit; D = Display Nonuniformity; E = Pixel Defect; F = Breaking and Cracking; G = Others

MANUFACTURING EQUIPMENT

A large infrastructure of AMLCD equipment suppliers is being established in Japan. A summary of the principal suppliers is shown in Table 3.5.

PECVD

In-line vertical two-sided deposition systems are used to deposit a-Si and the gate dielectric insulation layer (SiN or SiO₂). Anelva, with over 80% of the world market, dominates this business. In-line deposition systems have multiple vacuum chambers connected via gate valves. Substrates are loaded in the window-frame-like trays that

Table 3.6
Major Equipment Suppliers

PECVD (Multichamber Batch)	Anelva Shimadzu Ulvac
Sputtering (Continuous Multichamber)	Anelva Ulvac Leybold Shimadzu
Dry Etch (Single Substrate)	Anelva Ulvac Tokuda
Lithography (Cassette-to-Cassette)	Nikon Canon Dai Nippon Screen (MRS)
Wet Processing (Cleaning, Etching & Resist Coating)	Dai Nippon Screen Chuo Riken

At Least-

- 90 TFT-related manufacturing equipment suppliers
- 60 Test and inspection equipment suppliers
- 90 Materials suppliers - substrate, liquid crystal, polarizers, filters, etc.

hold up to four substrates and are clamped against the substrate holder. The vertically-held substrates are transported into vacuum chambers. The first one or two chambers contain quartz heater lamps to elevate the substrate temperature to 300-350°C. Several deposition chambers follow the heater chamber, as shown in the schematic of Figure 3.5. SiN, a-Si and SiN, or N + a-Si are deposited consecutively in the process chambers. The first SiN layer is deposited in a NH_3/SiH_4 plasma with the substrates held at 300-350°C. The lower deposition temperature of the a-Si layer necessitates the incorporation of a cooling chamber in order to maintain a short tact time (10-minutes). A cross-section of the deposition chamber is shown in Figure 3.6. The voltage is applied to maintain the plasma. The substrate holder straddles a heater to maintain the elevated substrate deposition temperature.

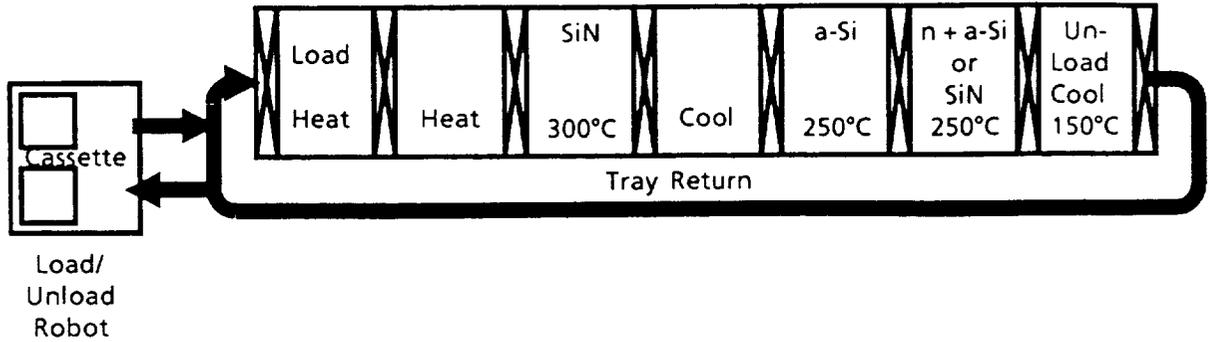


Figure 3.5. ILV-9300 P-CVD System

The following list summarizes the capabilities of the Anelva 8-chamber CVD system:

- o 8 substrates (300 x 400 mm) per chamber, 4 on each side
- o 10 minutes tact time
- o 10% deposition uniformity
- o 4-8 particles/square inch (without deposition) for one pass through the system
- o mechanical cleaning is required, resulting in 30 hours downtime
- o particle monitoring in vacuum ports of load and unload chambers

After deposition, the substrates exit the unloading chamber and return to the front end of the chamber through a clean tunnel. The substrates stay in the tunnel for 30-60 minutes to cool. The PECVD system is normally situated in a service chase, with the load station and unloading platform of the tray protruding into the clean room.

Automated loading, particle levels, and downtime require considerable improvement.

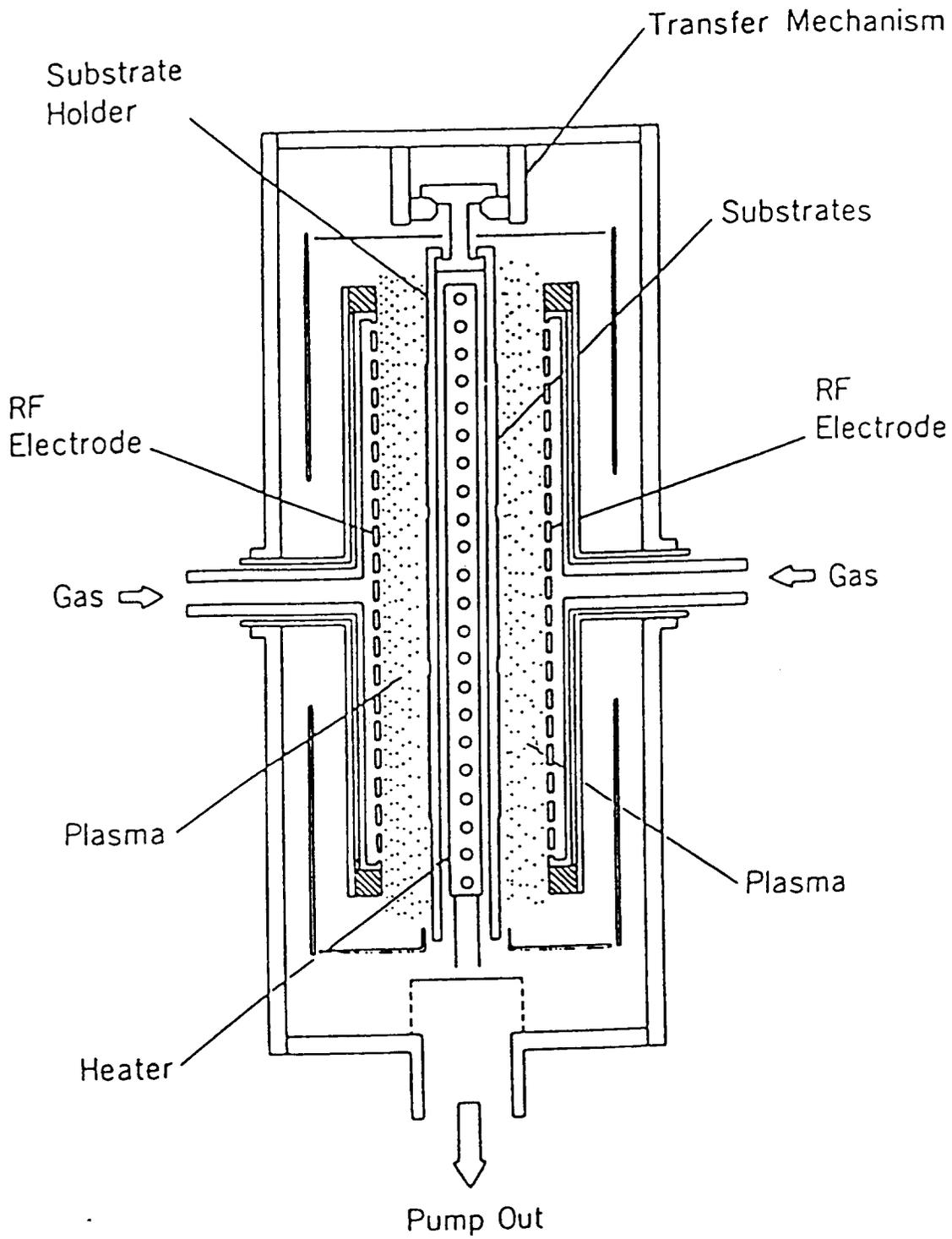


Figure 3.6. Vertical Double-Sided Deposition Chamber

Sputtering

Horizontal transport sputtering systems are commonly used for data and scan metal lines as well as ITO. A typical ITO deposition system is shown in Figure 3.7. Very large systems containing many substrates can be deposited simultaneously. Chamber cleaning in sputtering systems, target exchange, and cryo-pump regeneration are the most time-consuming maintenance factors. A comparison of the factors that affect tact time in sputtering and PECVD is shown in Table 3.6.

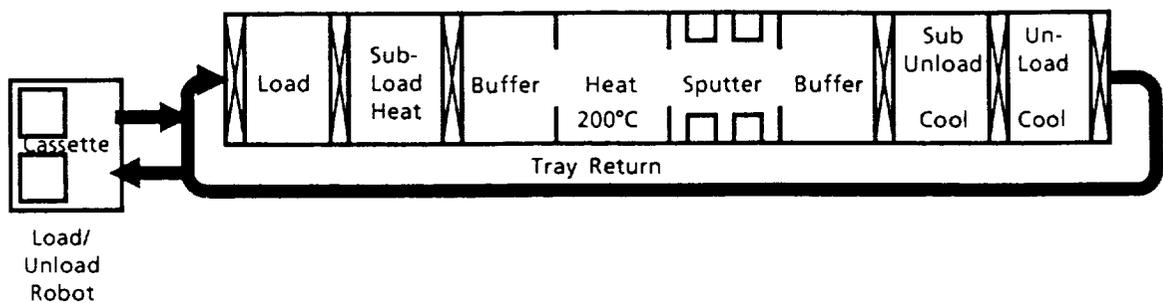


Figure 3.7. Sputtering System

Lithography

In a multimask process, photolithography productivity is critical. The two major Japanese mask aligner vendors, Nikon and Canon, have developed large-area aligners that are essentially derivatives of their IC exposure systems.

Nikon developed a 1:1 stepper capable of expensive large substrates using a step-and-repeat system. It utilizes standard 6-inch reticles and a stitching accuracy of $1.5 \mu\text{m}$ or better. The stitching accuracy is particularly important because significant errors can lead to grey scale shift across the stitching boundary, which can be quite visible. Several different masks are needed to produce the required patterns across the substrate. The reticle change time, exposure time, and substrate movement and alignment time all contribute to the throughput of the system. Nikon is at present the dominant vendor for large-area photolithography systems.

Table 3.6
Factors Which Determine the Tact Time

	Sputtering	PECVD
Deposition Rate	●	○
Film Thickness	●	○
Contamination	●	○
Mechanical Transfer	●	●
Heat/Cool Speed	●	○
Evacuate/Vent Speed	○	●
Substrate L/UL Speed	○	●

● = Much Influence

○ = Little Influence

Canon has developed a 1:1 mirror projection system in which a slit scans and exposes the photo mask and substrate. Large masks enable a large slit width, which produces a single exposure for a VGA display and avoids the issues of stitching. Because 10-inch panels need no reticle change, this technique has potentially high throughput, but mask costs are extremely high. This stepper is not yet widely used and does not yet appear to be performing as expected.

The MRS Stepper sold in Japan by DaiNippon Screen is now under evaluation in various companies. It is a 2:1 stepper that achieves high throughput by exposing two images at once through double-barrel optics. It has impressive built-in metrology and very user-friendly software. The magnification can be varied to compensate for substrate shrinkage. This system performs well; it is imported from the United States.

The critical challenges for photolithography are to further improve throughput while increasing stitching and alignment accuracy to satisfy future requirements for high-resolution displays. One possible approach to increase throughput is to use a large-area proximity aligner for noncritical layers. However, mixing and matching of proximity and stepper aligners has many issues. Proximity aligners could be successfully used for color-filter fabrication.

The Giant Technology Corporation is developing a printing technology for pattern formation. This is an interesting approach, but is still in its infancy.

Wet Processing & Cleaning

Cleaning processes are one of the key factors in achieving higher yield. Around 80% of the defects come from particles on the substrate, which are almost impossible to completely eliminate. Cleaning prior to deposition and resist coating is very important. Particles greater than $1\ \mu\text{m}$ are more important to remove than submicron particles. The importance of the cleaning methods at each step of the TFT process is described in Table 3.7. The key cleaning processes in the LCD process occur prior to polyimide alignment film coating and after rubbing the film. As freon cleaning is being phased out, alternative cleaning processes are being sought.

Table 3.7
Importance of Cleaning at Each Step

	Particles	Organic Contaminants	Inorganic Contaminants	Surface Topology
Glass Substrate Prep.	B	B	C	B→C
Before Deposition	B→A	B	C→B	B
Before Resist Coating	B→A	B	C	C
After Resist Removal	B	B	C	C

where: A is the highest in performance
B is medium
C is the lowest

The cleaning methods and processes are summarized in Tables 3.8 and 3.9. For cleaning particles larger than $2 \mu\text{m}$, 70% are removed by brushing with the aid of a surfactant and low-pressure water spray to avoid damage. Roller-brush cleaning has the problem of leaving 100-300 particles on the back side of the substrate 5-7 mm from the edge. Disk brushing has recently proved to be superior, leaving fewer than 30 particles on the back side of the substrate. At present, during cleaning the substrate is often held around the edge. However, as the substrates become larger and possibly thinner (0.7 mm), they will need to be supported in the middle; this factor will cause further cleaning problems. The Megasonic method, which combines cleaning spray with ultrasonic energy, removes 90% of particles down to $0.3 \mu\text{m}$ and cleans off the surfactant. The various features of cleaning techniques are summarized in Table 3.10. Substrate charging problems have been associated with jet spraying equipment.

Table 3.8.
Cleaning Processes Used for TFT LCD

Category	Cleaning Method	Features	
WET CLEANING	Brush Scrubbing	Removes stubborn particles; not suitable for smaller particles; effect is proportional to brushing pressure	
	Physical Cleaning	Jet Spray	Suitable on patterned, hydrophilic, and soft surfaces; requires caution regarding static charge; ineffective without high water pressure
	Ultrasonic Cavitation	Accelerating effect of chemical washing is conspicuous, has difficulty eliminating particles; requires caution regarding cleaning unevenness due to generation of standing waves	
	Megasonic (1 MHz)	Can eliminate submicron particles when used with chemical cleaning fluid; strong rectilinear propagation of sound waves, requires caution around jig structure	
Chemical Cleaning	Organic Solvent	Suitable for eliminating multiple contamination of organic substances; solvent is chosen depending on contaminant; difficulty with high level of cleaning	
	Neutral Detergent	Suitable for contamination from particles and organic substances; no damage to material being cleaned; difficulty is that interface activator adsorption layer remains	
	Chemical Cleaning Fluid	Depending on the orientation constituent, it acts in etching, oxide decomposition, hydrophilic surfaces, and ionization; suitable for all contaminants; needs chemical management	
	Pure Water	Eliminates chemicals after chemical processing; cleaning capability depends on water purity; insufficient for particles and organic substances	
DRY CLEANING	Ultraviolet Ozone	Eliminates organic contaminants at the adsorption film level; improves coverage prior to resist application	
	Plasma Oxide	Applies to eliminating organic substances such as photoresist, not suitable for particles and nonorganic contaminants, low throughput	
	Non-oxide	Eliminates slight organic and inorganic contaminants; allows for highly clean surface; equipment is expensive, low throughput; limited application	
	Laser	Localized selective cleaning, not suitable for full surface cleaning	

Source: Nikkei BP

Table 3.9
Cleaning Process and Method

Process	Purpose	Method
Glass Substrate	Particle Removal	Brush, Ultrasonic
	Contaminants	Organic, Neutral Detergent Water
Before Deposition	Micro Crack	Chemical Etching
	Particle	High Pressure Jet, Ultrasonic
Before Resist Coat	Organic	Organic, Neutral Detergent Water, Plasma
	Inorganic	Chemicals
	Surface Etch	High Pressure Jet, Ultrasonic
After Resist RMV	Particle	UV/O3, Neutral Detergent Water
	Organic	Chemicals
	Inorganic	Chemicals
After Resist RMV	Residuals	Chemicals
	Resist Removal Material	Chemicals
	Pattern Edge Correction	Chemicals

Table 3.10
Cleaning Techniques and Features

	Features						Handling	
	Particle Size (μm)	Damage	Charging	Contamination	Stepped Surface	Spin	In-Line Conveyer	Batch
Brush	> 10	Large	Small	Large	No	Yes	Yes	N/A
Jet	> 5	Medium	Large	Large	Yes	Yes	N/A	N/A
US Cav.	> 3-5	Large	Small	Small	Yes	N/A	Yes	Yes
US Vib.	< 3	Small	Small	Small	Yes	Yes	Yes	Yes

Jet High Pressure Water Jet
 US Cav. ... Ultrasonic Cavitation
 US Vib. ... Ultrasonic Vibration

A typical spray process line is shown in Figure 3.8. Spinning is the dominant technique used to deposit photoresist. With a spinner incorporating a proximity plate above the substrate, 4% resist uniformity can be achieved. Efficient resist usage is important for cost reasons: 15-30 cc of resist per substrate is sufficient to obtain good uniformity. Another critical issue is throughput; at present, resist coating is achieved at a rate of 1 substrate per minute. A DaiNippon Screen process line is shown in Figure 3.9.

A complete cleaning, exposure, developing, and etching line is shown in Figure 3.10. Such complete lines are not used in manufacturing because the processes are not yet mature and need further development. DaiNippon Screen is the major supplier of wet processing equipment. A complete image photo process with AGV is shown in Figure 3.11.

Dry Etching

Dry etching can provide much better line-width control, but, because it is a single-plate process, it is extremely slow. Considerable development is required to improve throughput for this process. Today's TFT labs require a very large number of dry etchers.

Cell Fabrication

Various custom-built equipment has been developed, including space sprayers and rubbing machines for alignment layers.

Substrates

Low-alkali-content Corning 7059 substrates, made by the fusion method, dominate AMLCD, with over 90% of the market. At present, the glass finishing process is as follows:

- o beveling and cutting corners
- o washing
- o inspection
- o polishing
- o washing
- o inspection

The fusion process produces a very high-quality finish that is, in principle, better than a polished surface. However, because the sheet is often damaged in the later finishing process, the substrates must be polished. In an effort to reduce cost, Corning developed a new process that preserves the fusion-quality finish, eliminating the necessity for polishing and the subsequent washing and inspection.

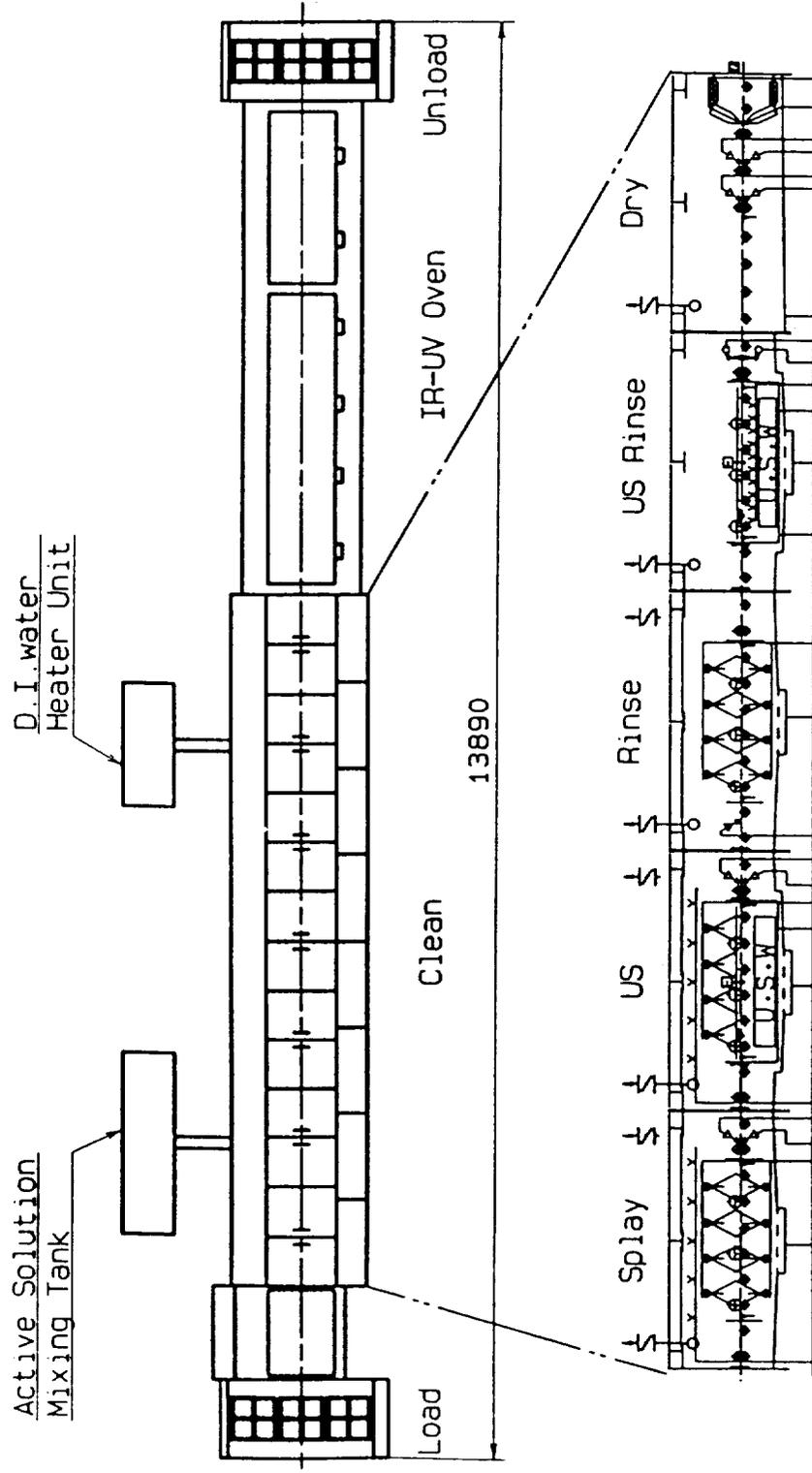


Figure 3.8. Process Line

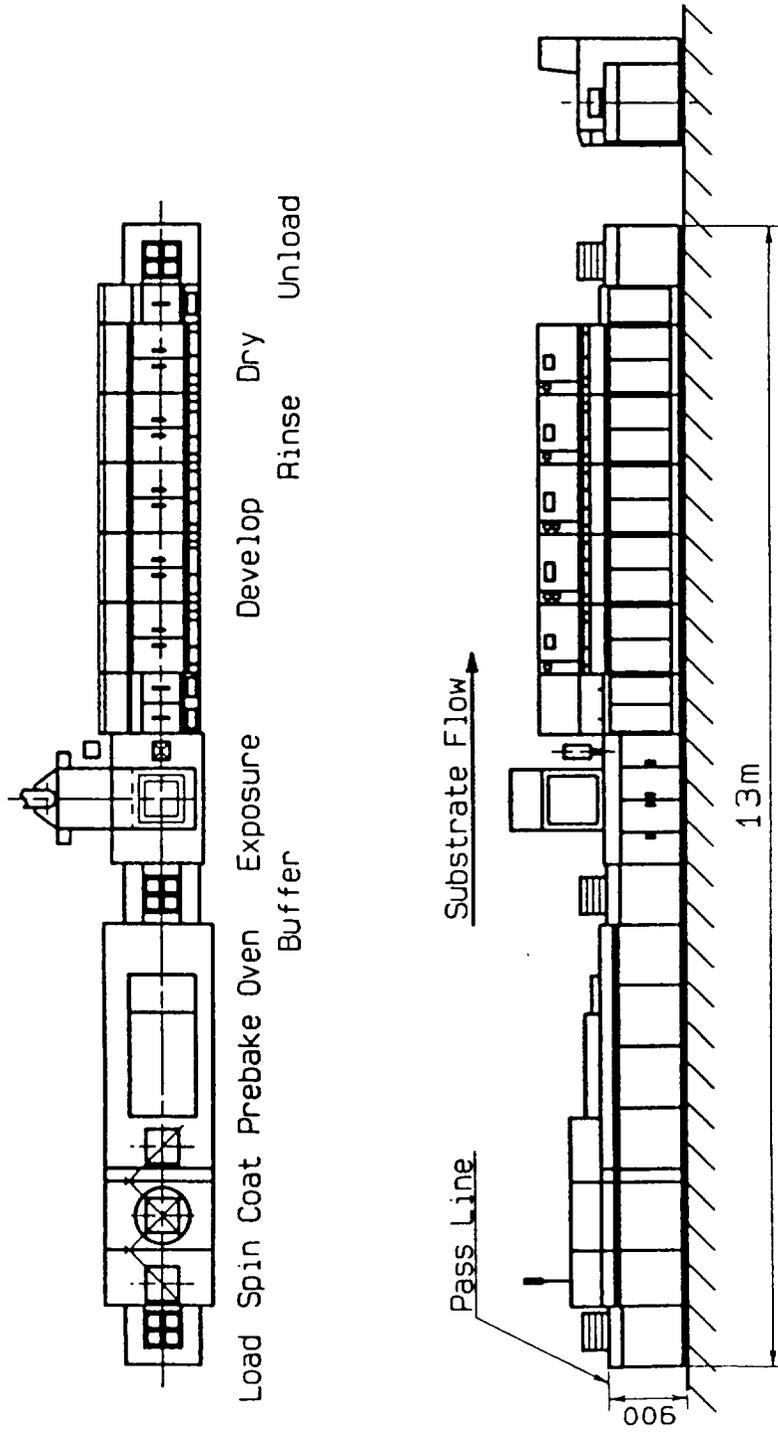


Figure 3.9. Photo Process Line

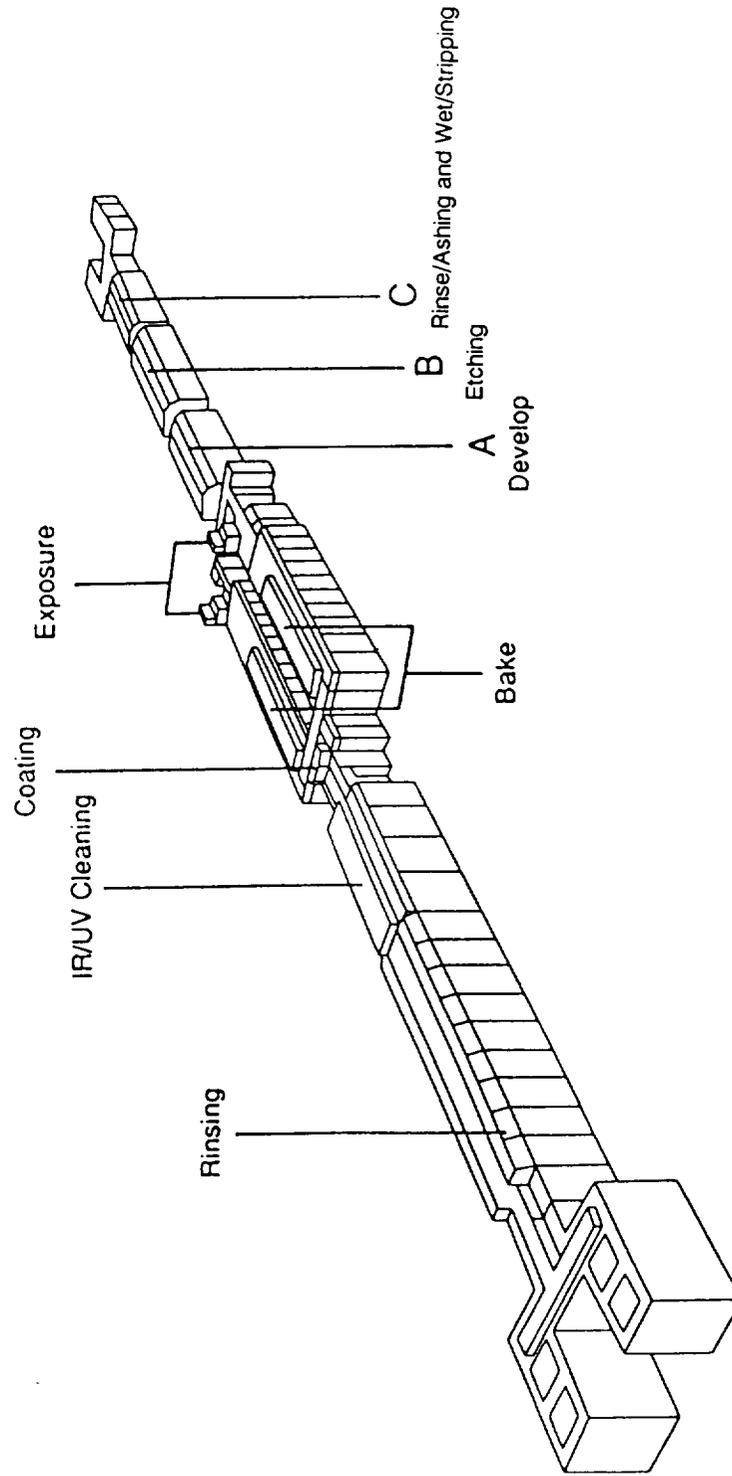


Figure 3.10. Rinse/Wet Processing Line

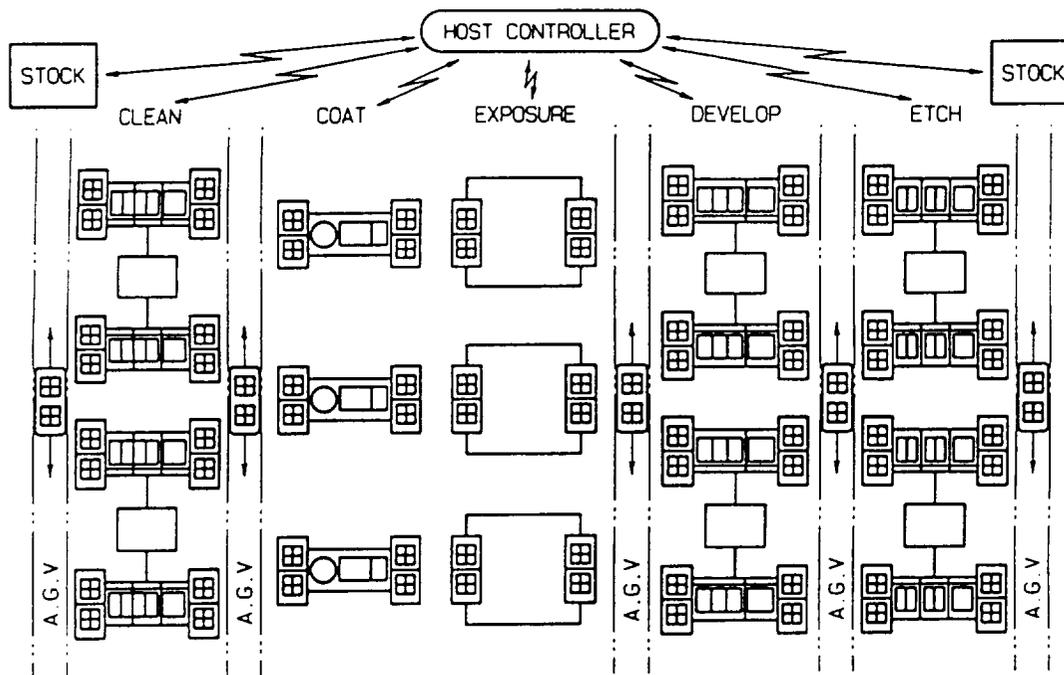


Figure 3.11. General Image of Layout

The glass substrates are preshrunk by annealing and are slowly cooled to minimize dimensional changes during the temperature cycling of the TFT processes.

Table 3.11 summarizes the properties of available glass substrates. NEG OA2, Hoya NA40, and Corning 1733 are particularly interesting glasses with higher softening points than 7059, thus reducing shrinkage or maybe enabling the use of high-temperature processes such as low-temperature p-Si.

Drivers and Packaging

The establishing of a quality packaging technology is essential for AMLCD. As the resolution of the display increases, so does the need for low-cost higher density packaging. Table 3.12 and Figure 3.12 compare three types of packaging: chip-on-board, TAB, and chip-on-glass. At present, TAB, with an isotropic adhesive, is the mainstream approach for VGA AMLCD. The minimum pitch is 80-100 μm . Compact, thin LCD modules can be achieved because the TAB IC are positioned on the sides of the backlight.

Table 3.11
Properties of Glass Substrate

Glass code	Type	Reference temperature		Thermal expansion $\times 10^{-7}/^{\circ}\text{C}$ (0-300°C)	Density g/cm ³
		Strain point °C	Annealing / Softening point °C		
Corning 7059	Barium aluminoborosilicate	593	639	46	2.76
Hoya NA45	Borosilicate	610	658	46 (100-300°C)	2.78
Hoya NA35	Borosilicate	650		37 (100-300°C)	2.50
Asahi AN	Alkaline-earth aluminoborosilicate	616	661	43 (50-200°C)	2.72
NEG OA2	Alkaline-earth-zinc aluminoborosilicate	635	685	47 (30-380°C)	2.76
Corning 1733	Alkaline-earth boroaluminosilicate	640	689	36.5	2.49
Hoya NA40	Alkaline-earth-zinc-lead aluminosilicate	656	708	43 (100-300°C)	2.87
Corning 1724	Alkaline-earth boroaluminosilicate	674	721	44	2.64
Corning 1729	Alkaline-earth aluminosilicate	799	855	1107	2.56

Table 3.12
Comparisons of Packaging Configuration

	OLB	Bonding Pitch	Packaging Size	IC Repair	Reliability	Packaging Cost
CHIP ON BOARD	Heat Seal	Δ	Δ	Δ	Δ	Δ
	Rubber	X	X	○	X	Δ
CHIP ON FPC	ACF	○	○	Δ	○	○
	UV Resin	○	○	Δ	○	○
CHIP ON GLASS	-	●	●	?	?	●

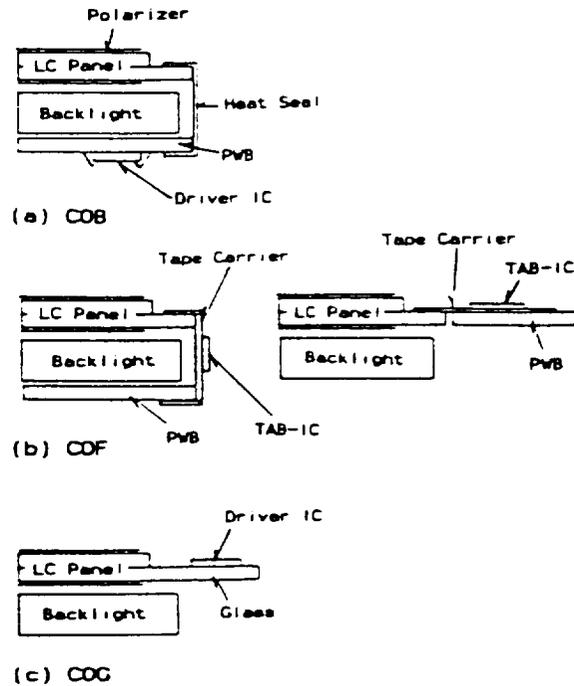


Figure 3.12. Packaging Configuration in LCDs

Chip-on-glass (COG) will be used in high-resolution projection LCDs; COG configurations are shown in Figure 3.13. The IC bonding methods are classified roughly into conductive rubber connection, metallic connection, and conductive resin adhesive. The COG technology that can assemble IC chips onto ITO terminal leads and also repair the inferior IC is strongly preferred.

Eight-level, 120-output-driver ICs have been developed at Sharp, NEC, and Hitachi. TI Japan and others are developing a 16-grey-level 192-output chip.

CONCLUSIONS

That Japan has apparently made a strong national commitment to AMLCD technology is evident from the large investment in new manufacturing plants by the leading companies. For this reason, an extensive materials and manufacturing equipment infrastructure is being established. There is still considerable work to be done on manufacturing issues to reduce cost. Up-time of equipment and achieving high yield are the main barriers limiting production.

An impressive array of high-quality AMLCDs is being produced in Japan. The overwhelming sense is that there is a new business emerging that is still in its infancy. Many large Japanese companies have made a strong financial commitment to this business. A strong dedication and focus on implementation, which Japanese companies have been so successful at in the past, will make this business successful. It is also clear that no technical discontinuity has been used to achieve this goal. There is no magic here, just good manufacturing practice.

Bonding configuration									
Bonding method	Rubber connector	Solder	In alloy	Conductive paste	Conductive paste	ACF			
Driver IC	Au bump	Sn/Pbbump	Au/Inbump	Cu/Aubump	Au bell	Au bump	Au bump	Al pad	Conductive particle
LC panel	100-300um	200-300um	50-150um	100-150um	60-130um	150-200um	< 50um	60-130um	50-300um
	ITO	Au	ITO	ITO	ITO	ITO	ITO	ITO	ITO
Temp.	RT	300-350°C	120-150°C	100-120°C	100-120°C	160-180°C	RT	150-200°C	RT
Bonding Pressure	< 5 g/pad	-	< 20 g/pad	1-2 g/pad	< 50 g/pad	20-50 g/pad	10-20 g/pad	10-20 g/pad	-
	-	-	-	-	-	-	UV light	-	UV light
Repeatability	O	x	O	O	O	Δ	O	Δ	O

Figure 3.13. Various IC Bonding Methods

CHAPTER 4

PASSIVE MATRIX LIQUID CRYSTAL DISPLAYS

Thomas L. Credelle

INTRODUCTION

Liquid crystal displays (LCDs) have become commonplace in all aspects of our "information age." Uses range from wristwatches to computer displays to television. The most common type of LCD is the simple matrix twisted nematic LCD, although active matrix LCDs are becoming more common, especially in applications that require high-performance displays. A simple matrix LCD can be defined as an LCD that is addressed by applying voltage pulses directly to electrodes on either side of the liquid crystal molecules. This section of the report details the status and future prospects for passive matrix LCDs. The passive matrix LCDs covered in this report are twisted nematic, supertwisted nematic, vertically aligned nematic, and ferroelectric. Other LCDs have been investigated, but these are the main types either in use or under active development in Japan today. An important class of LCDs not covered here is polymer dispersed LCDs (PDLCs), because PDLCs are not multiplexible into high-information-content LCDs. The materials developments are covered in Chapter 2, and the use of the materials in conjunction with active matrix substrates is covered in Chapter 6, Projection Displays.

LCD BASICS

Liquid crystals are organic molecules that have crystal-like properties but that are liquid at normal temperatures. Because the intermolecular forces are weak, the molecules can be oriented by weak electromagnetic fields. The liquid crystal molecules used in LCDs also have an optical anisotropy (different indices of

refraction for different axes of the molecule) that is used to create visible images. The most common LCD is based on nematic liquid crystals, but displays under development are based on other phases, particularly the ferroelectric smectic phase.

TWISTED NEMATIC LCDS

Liquid crystals were actually discovered over 100 years ago, but they did not find commercial applications until the invention of the twisted nematic (TN) LCD by Schadt and Helfrich in 1971 (Schadt and Helfrich, 1971). Nematic liquid crystals have a short-range order and have some of the properties of uniaxial crystals. In the natural state, the molecules have no long-range order and so scatter light. If the molecules are oriented, however, they can become transparent with crystalline optical properties. In a typical LCD, the molecules are aligned by mechanically rubbing polyimide layers on two pieces of glass. In the TN cell, the alignment is at right angles between the two inside surfaces on the glass. A small amount of cholesteric LC is usually added to encourage twisting in one direction only. The aligning layer usually causes a small tilt on the LC molecules at the surface, typically $1-3^\circ$; this effect can be important in determining maximum contrast ratio or response time.

In a typical TN LCD, illustrated in Figure 4.1, crossed polarizers are aligned parallel to the rubbing direction. Polarized light is transmitted and rotated by the liquid crystal molecules if the product of Δn (birefringence) and cell spacing is much greater than half the wavelength of the incident light. For the condition of crossed polarizers, the light is transmitted through the second polarizer. If an electric field is applied to the transparent conductors, the molecules rotate and the light transmits through the cell without rotation. The second polarizer absorbs the incoming light and the cell appears dark. If the second polarizer is aligned parallel to the first, then light is transmitted with an applied field.

The transmission of the LCD as a function of applied voltage is shown in Figure 4.2. There is a threshold behavior for most LCDs and no change in transmission occurs until a threshold voltage, V_{th} , is reached. Transmission then decreases as the voltage increases until saturation is reached. Threshold voltage is typically 1.5-2.5 volts, and saturation occurs at about 4-5 volts. Much research has gone into both lowering the threshold voltage and increasing the sharpness of the transfer curve. It should be noted that the LCDs show an rms response because of the slow response of the LC and the fact that the LC molecules have a very weak dipole moment.

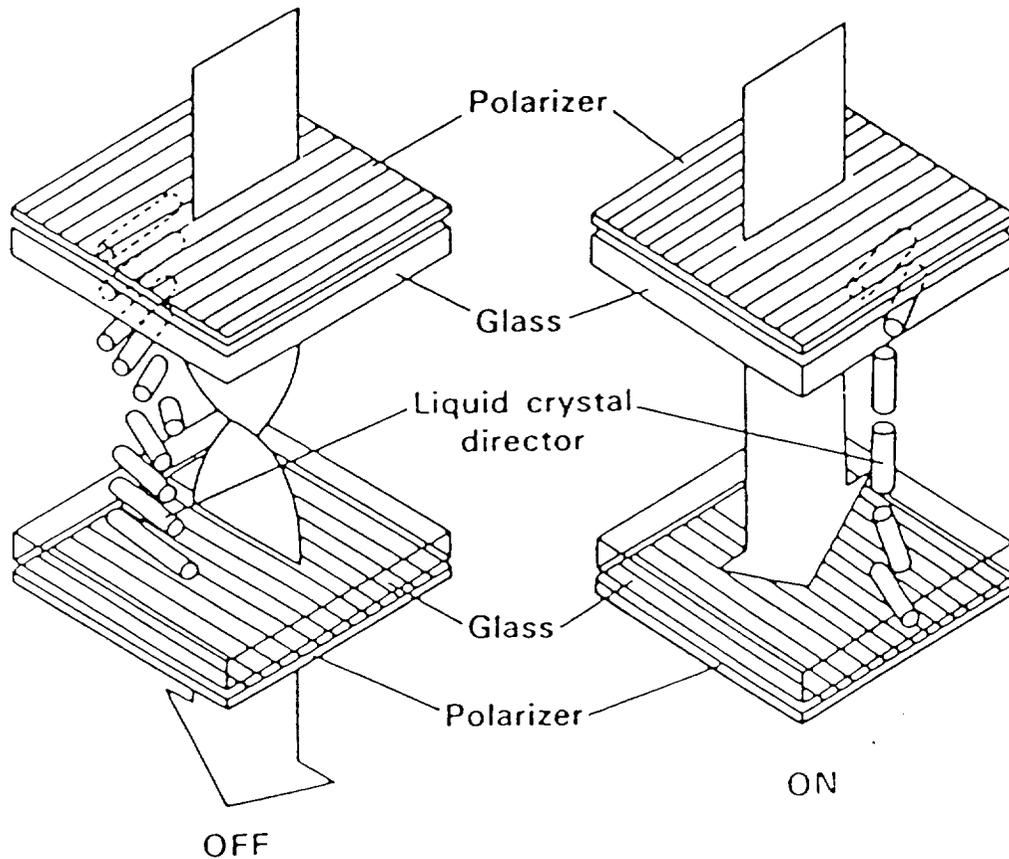


Figure 4.1. Typical Twisted Nematic LCD (Normally White Mode)

For direct-drive LCDs, such as are used in simple indicators, high contrast can be achieved by driving the LC into saturation. Contrast ratios in excess of 100:1 can be achieved in this mode. To address multiple lines, as is typical in computer or TV screens, multiplexed addressing is used. Information is applied to column electrodes one row at a time. The number of lines that can be multiplexed depends on the steepness of the transfer characteristic, as has been described by Alt and Pleshko (1974). The ratio of the voltage in the selected state, V_s , and the nonselected state, V_{ns} , is given by

$$V_s/V_{ns} = \sqrt{(\sqrt{N} + 1)/(\sqrt{N} - 1)}$$

where N is the number of rows multiplexed. For example, if $N = 200$, the difference between on and off states is only 7%; to achieve reasonable contrast ratio, a very steep electro-optic transfer characteristic is required. The limit for TN LCDs is about 64:1 multiplexing; supertwisted nematic LCDs have a much steeper characteristic and can be used with multiplexing ratios up to 480:1.

SUPERTWISTED NEMATIC LCDS

The biggest problem with early multiplexed LCDs was the reduction in contrast ratio with number of addressed lines. This problem was essentially eliminated with the invention of the supertwisted nematic (STN) LCD in the early 1980s. It was found that if the twist angle was increased to 270° , the slope of the brightness-voltage curve approached infinity; under this condition, a large number of lines could be multiplexed. This higher twist angle was achieved by adding higher concentrations of cholesteric liquid crystal to the nematic mix and by increasing the tilt angle at the glass surface.

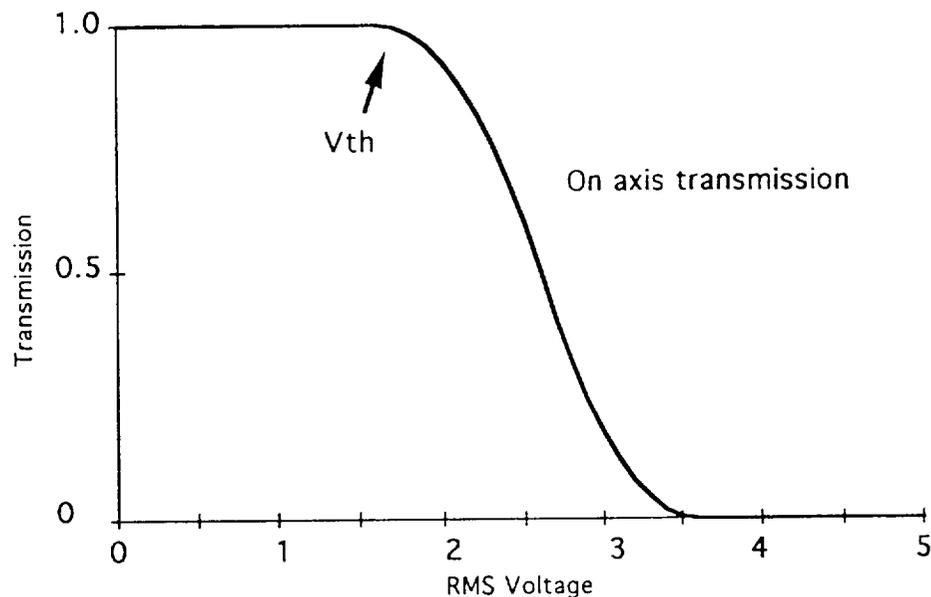


Figure 4.2. LCD Transmission (Brightness) As a Function of Applied Voltage

The first successful STN LCDs used a birefringence mode to create a "yellow mode" and a "blue mode." (Scheffer and Nehring, 1984) Although the result was not optimum for general display use, it was possible to demonstrate 200:1 multiplexing with >5:1 contrast ratio. For the first time, LCDs could be seriously considered for use in portable computers.

The next advance was the development of compensated STN LCDs to produce true black-and-white images. Using either a second STN LCD with opposite twist or a retardation film, several manufacturers were able to produce black-and-white LCDs with high contrast and multiplexibility. Today, the film-compensated STN (FSTN) is preferred because of its thin profile and low weight compared to the double STN (DSTN) type. FSTN LCDs with multiplexing ratios as high as 480:1 have been demonstrated in both black and white and full color. Full color is achieved in the same manner as in active matrix LCDs; that is, RGB filters are patterned on one of the glass plates to control the color of the light transmitted through the LCD.

VERTICALLY ALIGNED NEMATIC LCDS

The vertically aligned nematic (VAN), which is also known as the electrically controlled birefringence (ECB) effect, was first described in 1971 but was inferior to the twisted nematic effect. VAN LCDs require homeotropic alignment of the liquid crystal molecules at the glass surface (long axis is perpendicular to the surface) and a negative dielectric anisotropy. Both conditions have been hard to achieve until recently. The principle of operation is based on a change in birefringence induced by tilting the molecules with an applied field. A steep threshold characteristic can be achieved with careful control of the surface tilt angle and the cell spacing and by using liquid crystals with specific elastic constants (high ratio of bend/splay elastic constants). Full-color VAN LCDs were demonstrated by Stanley Electric Company at the Japan Electronics Show.

FERROELECTRIC LCDS

The LCDs described so far are all based on nematic liquid crystals. A second major class of LCDs under development is called the ferroelectric LCD because the molecules have a permanent polarization. Ferroelectric LCDs are smectic liquid crystals that have a natural layered order. Most ferroelectric LCDs are in fact of the smectic C phase (SmC) and possess a chiral behavior. Typically, the ferroelectric LCDs are built with very small cell gaps (1-2 μm) to stabilize the alignment of the molecules. The alignment layers cause a perpendicular alignment of the smectic phases in a "bookshelf" geometry. In the thin cells, there is a net polarization that is perpendicular to the glass plates; this polarization can couple to an externally

applied field to rotate the molecules either "up" or "down." Because the liquid crystal molecules have an optical anisotropy, the state of the molecules can be "read" with external polarizers. Ferroelectric LCDs have several interesting properties that make them desirable for display applications: (a) the molecular rotation is fast--50-100 μ sec, (b) the effect is bistable, and (c) the viewing angle is wide because of the small cell gap. LCDs with up to 1000 lines have been produced in both color and monochrome (Canon). One drawback for some applications is the lack of gray scale except by time multiplexing; this severely limits applications for TV. Another drawback is the sensitivity of the alignment to shock and vibration. Because they allow high-speed switching, ferroelectric LCDs are also of interest to the electro-optic community as optical switches. Another interesting application is for print heads to replace scanning laser beams; in this case, the LCD acts as a shutter and is used with a light bar as a fluorescent lamp.

STATUS AND PROSPECTS FOR THE FUTURE

The JTEC team visited the major suppliers of LCDs in Japan and reviewed the published literature on the subject. It based its conclusions about the status and future prospects for each of the major types of LCDs on the visits and the literature review. In cases where there was not general agreement, I have tried to present all sides of the issue.

Twisted Nematic LCDs

Despite their limitations, TN LCDs are still the most widely used LCD type in use today. They are used extensively in watches, calculators, games, instrumentation, and "personal information products." They are the lowest cost LCD and are the lowest power (in reflective mode) flat-panel display ever developed. TN LCDs will continue to be used in applications where cost, size, and power are important, and especially in "direct-drive" (no multiplexing) applications, where the contrast and brightness can be quite high. TN LCDs will be gradually replaced by FSTN LCDs in applications where multiple lines of data are required.

The main research topics in Japan in the field of TN LCDs are materials improvements to widen the temperature range for automotive and outdoor applications, lower voltage switching to reduce the power and circuit cost, and, of course, lower overall cost.

Supertwisted Nematic LCDs

STN LCDs and, in particular, FSTN LCDs are the LCDs of choice for office automation applications. As their cost comes down, they are finding their way into an ever-increasing number of applications. The performance of the FSTN LCD is

good in multiplexing ratios up to 240:1 and is adequate even at 480:1. Sizes up to a 17-inch diagonal have been demonstrated (Sanyo), with resolution up to 1024 lines. The contrast ratio has been extended to 20:1, and response time has decreased to the 100-150 msec range--a range that is more than adequate for mouse operation on portable computers. Viewing angle is still somewhat limited compared to active matrix LCDs, but improvements in retardation films have led to wider viewing angles. Response times as low as 50 msec have been demonstrated on small panels, so FSTN LCDs may be usable for limited video applications (e.g., slow-scan phone).

The main problems today are cross-talk, response time, and viewing angle. Cross-talk appears as a shadowing on the screen and gets worse as the multiplexing ratio increases. Response time, although it is adequate for portable computer use, must be improved for full video applications. Viewing angle is adequate for one-person viewing but not for viewing by larger groups.

The principal research topics for STN LCDs are understandably in the materials area. New materials with lower viscosity and higher ratios of bend/splay elastic constants are under development. The physics of surface anchoring is also under study to determine better ways to control surface tilt angle, which directly affects the uniformity of the LCD.

Several labs are working to develop electronic drive circuits to solve some of the optical problems. Asahi Glass reported a new drive scheme with which it has achieved 20:1 contrast with 50 msec response time on a 5.7-inch diagonal color FSTN LCD (method not disclosed). Sanyo uses double drive for the row drivers to reduce horizontal cross-talk.

LCD manufacturing methods are also being improved. For example, lower resistance transparent conductors are being developed to reduce cross-talk. More accurate control of cell spacing is also required to improve background uniformity, especially for thinner LCDs.

The addition of color filters to FSTN has created new markets but has caused more severe manufacturing problems. It was reported that nonuniform color filter flatness is a major problem in attaining high yield for color FSTN LCDs. At least one manufacturer (Sanyo) is now producing its own filters to control this problem. It is likely that other LCD manufacturers will begin to make their own filters as well.

The prospect for the future of FSTN is steady improvements and lowering costs. FSTN LCDs will dominate the LCD business in the next five years. Optical performance will improve to levels of 30:1 contrast, < 100 msec response times, and multiplexing ratios > 500. While optical performance will improve, FSTN will remain inferior to active matrix LCDs. Improvements in materials will lead to wider viewing angles and wider temperature ranges. Automotive applications will become

commonplace as costs come down. Packaging of the LCD module will also improve, and thinner, lighter FSTN LCD modules with backlights will be produced. TAB packaging will replace PCBs in order to accomplish this size and weight reduction.

Vertically Aligned Nematic LCDs

VAN LCDs have been demonstrated by Toshiba and Stanley, but the largest effort is at Stanley Electric Company, which has achieved full-color VAN LCDs with excellent viewing angle in sizes up to a 14-inch diagonal. Gray scale was demonstrated using frame rate control. The advantages of VAN, according to Stanley Electric, are easier manufacturing (cell gap control is not so critical) and wider viewing angle in gray scale. Problem areas today include slow response time (250 msec achieved), low transmission (1.5-2.0% for color VAN), and limited temperature range (not yet sufficient for automotive applications). A basic problem that continues to delay progress is the lack of materials for VAN; since the market is limited for the special liquid crystal mixtures required for VAN, there is not as much research going on in this area as in the other areas. Stanley received funding for this development work through a grant from the Japan Research and Development Corporation; one of the requirements for the grant is to establish a pilot line. Therefore, Stanley will produce limited quantities of the VAN LCDs. Because of the low transmission efficiency, use will be limited to AC-powered monitors; therefore, primarily the larger sizes are of interest. The slow response time will further limit their use to nonvideo applications.

The general feeling among the Japanese LCD suppliers is that this technology will be used only in niche markets, if at all. Toshiba said they had reduced their effort in this area. Stanley is continuing and will have some production capacity.

Ferroelectric LCDs

For the past several years, ferroelectric LCDs have held much promise as "the next" LCD to be commercialized. So far, however, manufacturing problems have kept the technology in the lab. Most LCD suppliers have research programs in ferroelectric LCDs, with Canon, Inc., at the head of the list. Our group did not visit Canon, but during our trip they announced both monochrome and color 15-inch diagonal ferroelectric LCDs and demonstrated them at the Japan Data Show in October 1991. The quality was reportedly excellent. The cell spacing is $1.5 \mu\text{m} \pm 0.05 \mu\text{m}$, which is a very severe tolerance. The report is that Canon will start manufacturing in 1992, but other LCD manufacturers greeted this announcement with some skepticism.

The problems facing ferroelectric researchers are numerous. The most important issues are alignment defect control (sensitive to shock and vibration), cell spacing control, temperature range, response time, and gray scale. New fluorinated liquid

crystal compounds are being developed to help decrease the response time and improve the contrast ratio (contrast is limited by defects). Sony is using a SiO evaporation for alignment layers to improve uniformity and contrast ratio; Sony is also developing gray scale techniques to address the video requirement.

Prospects for the future are mixed for this technology. While much research continues, it is unclear what market the ferroelectric LCD will serve. Certainly, if the problems can be solved, then the high contrast and wide viewing angle achieved with ferroelectric LCDs will put them in competition with active matrix LCDs. The biggest problem now is manufacturability; if Canon has solved this problem, then ferroelectric LCDs will be another viable LCD technology.

COMPARISON OF PASSIVE MATRIX LCD TECHNOLOGIES

The main attributes of the various passive matrix LCD technologies are summarized in Table 4.1. Diagonal size is limited by the size of the glass used in manufacturing; most manufacturers now have the capacity to produce up to a 17-inch diagonal. The number of vertical lines achievable depends on the multiplexing ratio; most FSTN panels are addressed as two panels so that a 480:1 multiplexing ratio results in a 960-line LCD. Ferroelectric LCDs are limited in a different way; since the effect is bistable, an unlimited number of lines can be addressed. The switching time, however, limits the number of lines if video response is required. For example, if the switching time is 50 μ sec, a 500-line LCD can be refreshed in 25 msec and a 1000-line LCD in 50 msec. Response time of the LCD is listed as the on time plus off time; this represents the best metric for portable computer use. The quality of color refers to the saturation and range of colors achievable (active matrix LCDs would earn a grade of excellent). Viewing angle quality is listed for single-user applications such as personal computers or personal TVs. Cost estimates are based on available data for the units in production and guesses for those not in production.

The main competition for passive matrix LCDs is the active matrix LCD; Table 4.2 compares the two types of LCDs. As Table 4.2 shows, active matrix LCDs win in almost every category except cost. It is the high cost of active matrix LCDs that limits their widespread use today.

CONCLUSIONS

Passive matrix LCDs dominate the flat-panel display business today and will continue to dominate it, at least in unit sales, for the next five years. FSTN LCDs have enabled a brand new industry (portable and notebook computers) and are also used widely in Japan in word processors. Color FSTN will continue to improve and will be introduced to the market in significant numbers in 1992-93.

Table 4.1
Comparison of Various Passive Matrix LCDs

TYPE	TN LCD	STN LCD	VAN LCD	FELCD	PDLC
DIAGONAL	UP TO 17"	UP TO 17"	UP TO 17"	UP TO 17"	UNLIMITED
RESOLUTION	64 LINES	480 LINES	480 LINES	1000 LINES	8 LINES
CONTRAST RATIO	> 100:1	> 100:1	> 50:1	> 50:1	> 10:1 (DIRECT VIEW)
DIRECT DRIVE	> 3:1	> 20:1	> 20:1	> 50:1	> 5:1 AT 8 MUX
MULTIPLEXED					
RESPONSE TIME (ON+OFF)	60 ms (VIDEO)	200 ms ("MOUSE SPEED")	400 ms (QUASI-STATIC)	0.1 ms (LINE ADDRESS)	100 ms ("MOUSE SPEED")
COLOR †	POOR	FAIR	GOOD	GOOD	FAIR
VIEWING ANGLE	POOR	FAIR	GOOD	GOOD	*
COST	LOW	MODERATE	MODERATE	HIGH	LOW
STATUS	MASS PRODUCTION	MASS PRODUCTION	DEVELOPMENT	DEVELOPMENT	R&D STAGE

† COLOR ACHIEVED WITH ABSORPTIVE COLOR FILTERS WITHIN THE LCD

Table 4.2
Comparison of Passive and Active Matrix LCDs

	PASSIVE	ACTIVE
CONTRAST	10-20	100+
VIEWING ANGLE	Limited	Wide
GRAY SCALE	16	256
RESPONSE TIME	100-200 ms	<50 ms
MULTIPLEX RATIO	480	>1000
SIZE	Up to 17"	<14"
MANUFACTURABILITY	Simple	Complex
COST	Moderate	High

FSTN LCDs have not reached their full potential, and improvements are expected in several areas within the next two years. Notably, monochrome FSTN LCDs in sizes up to a 17-inch diagonal with 1280 x 1024 pixels, contrast ratio > 20:1, response time < 150 msec, and 16-32 gray levels will appear in mass production. Approximate prices expected within two years are \$150 for a 10-inch diagonal VGA monochrome, \$500 for a 10-inch diagonal VGA color, and <\$1000 for a 14-inch XGA monochrome.

VAN LCDs have made impressive gains but will likely be limited to niche markets because of their slow response time and low optical efficiency.

Ferroelectric LCDs are under active development at a few laboratories, but only Canon has announced production plans. If Canon has solved the manufacturing problems, then these displays will give competition to active matrix LCDs, especially in the larger sizes (≥ 15 -inch diagonal).

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CHAPTER 8

ACTIVE MATRIX TECHNOLOGY

Arthur H. Firester

INTRODUCTION

If Japanese technology is to be assessed and understood, it must be viewed within the perspective of the business environment and investments that drive the technology and the technology's maturity.

Although research into active matrix technology began in Japan in the early 1980s, it is only within the last several years that there have been significant investments in early production capabilities. The costs of R&D, although substantial, are quite small compared with the investments that will be necessary for real production. R&D leads to basic understanding and, from a commercial perspective, to the development and ownership of seminal concepts and patents that can provide competitive advantage (even to the extent of excluding competition) and future licensing incomes. Since the investments are relatively low, R&D can be extended in time at little cost. Similarly, pilot production development, although an order of magnitude more costly, does not impose major time pressures on the business enterprise. Here, too, the business intent is to establish intellectual property and to develop the requisite data and confidence to take the next expansionary step. The next step, production investment, is 100 times costlier. Significant resources are committed to building production-scale facilities and staffing them with engineers, technicians, and production workers. Now there is tremendous pressure to develop marketable products to provide a return on these large investments. Each additional month without marketable production brings further negative cash flow. Each early month with marketable production provides competitive advantage in cost reductions through cumulative production learning curves.

This is the stage the Japanese are in now. At least 10 companies have made major investments. The markets are ready to absorb all of these production capacities if they can meet their yield and cost goals. In the highly competitive Japanese environment, the belief is that there will be only five significant production leaders and five secondary production followers. None of the companies wants to be in the second tier. It is this environment that sets the stage for the technology drive and development and, accordingly, for this chapter of our technology report.

In this chapter we will first provide a basic introduction to the active matrix technology; examine in more specific detail the investment and production environment; review the status of major active matrix technologies, with particular emphasis on the dominant one, amorphous silicon; discuss recent advances in these technologies and the growing R&D interest in polysilicon active matrix technologies; and, finally, review recent commercial products and prototypes.

BASIC ACTIVE MATRIX TECHNOLOGY

Over the past five years progress in active matrix liquid crystal displays (AMLCDs) has been spectacular. Five years ago the questions were whether these complex devices could be made and whether they would gain market acceptance. Today those questions have been answered affirmatively; the only remaining questions are how low the cost of AMLCDs can be, how fast they will penetrate the display market, and how good their ultimate performance will be.

Liquid crystal displays are inherently simple and are intrinsically capable of the high performance desired for many display applications. However, expecting adequate nonlinearity sufficient to operate high information content displays places an unreasonable burden on the liquid crystal (LC) material itself. The value of using nonlinear circuitry in series with the LC pixel (Lechner, 1971) was recognized quite early in the technology. The use of thin-film transistors (TFT) as the preferred nonlinear element is based on the pioneering work of Peter Brody (1973), the "father" of the TFT active matrix.

Although many active matrix technologies have been explored, the dominant ones today are hydrogenated amorphous silicon (a-Si) thin-film transistors, metal-insulator-metal (MIM) diodes, and low-temperature polysilicon (p-Si) thin-film transistors. Although a-Si TFTs were suggested quite early (LeComber, 1979), the first commercial product was a pocket TV that used polysilicon TFTs (Morozumi, 1985).

The active matrix is a method of addressing an array of simple LC cells--one cell per monochrome pixel. In its simplest form there is one thin-film transistor for each cell. This arrangement is shown in Figure 5.1.

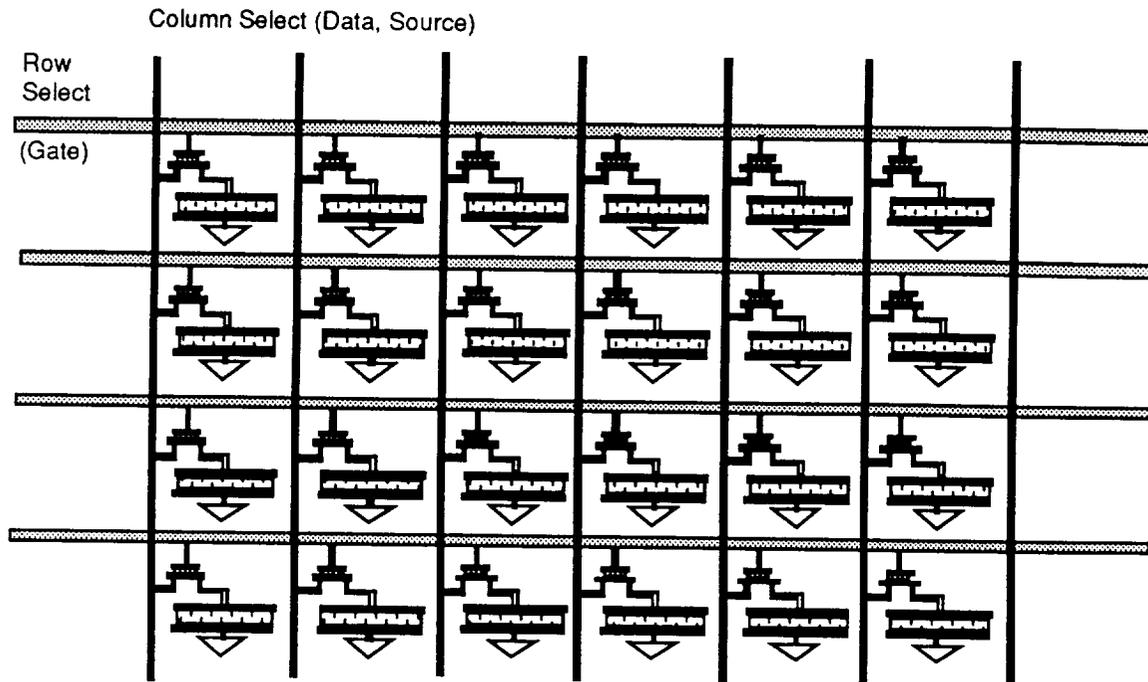


Figure 5.1. Simple TFT Active Matrix Array

A row of pixels is selected by applying the appropriate select voltage to the select line connecting the TFT gates for that row of pixels. When a row of pixels is selected, we can apply a desired voltage to each pixel via its data line. When a pixel is selected, we want to apply a given voltage to that pixel alone and not to any nonselected pixels. Those nonselected pixels should be completely isolated from the voltages circulating through the array for the selected pixels. Ideally, the TFT active matrix can be considered as an array of ideal switches. The operation of this active matrix would be as follows:

1. Appropriate select voltages are applied to the gates of the first row of the TFTs while nonselect voltages are applied to the TFT gates in all other pixel rows.
2. Data voltages are applied at the same time to all of the column electrodes to charge each pixel in the selected row to the desired voltage.
3. The select voltage applied to the gates in the first row of TFTs is charged to a nonselect voltage.

4. Steps 1-3 are repeated for each succeeding row until all of the rows have been selected and the pixels charged to the desired voltages.

All rows are selected in one scanning period. Thus, if there are 500 lines and the time to load data into each selected line is 50 μsec , then a single scanning period is 25 msec, for a field-scanning rate of 40 Hz.

The performance required of the TFTs in the active matrix depends on the display performance requirements--number of lines, number of gray levels, operating temperature, pixel density, and so forth. The TFT should behave as an ideal switch--zero *on* resistance and infinite *off* resistance. We can plot actual TFT on-current per micron of channel width and off-current per micron of channel width as a way to compare different TFTs and to predict their suitability for differing display applications (Firester, 1987). Figure 5.2 is this type of plot with a number of reported TFT data. An "ideal" TFT would be in the upper left corner of this chart.

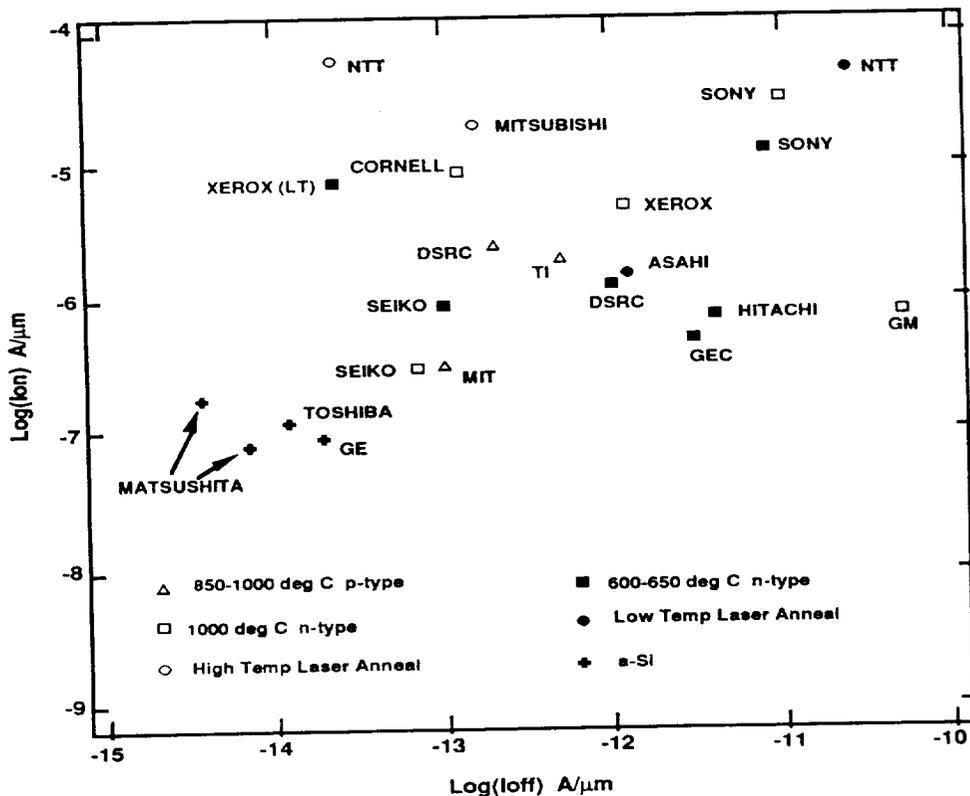


Figure 5.2. TFT Leakage and Drive Characteristics

The need for address and data line drive circuitry is another general aspect of active matrix displays that should be considered. A 1000 x 1000 simple monochrome active matrix has 1 million TFTs and requires 2000 connections to external drive circuitry. Currently these external circuits use flex-printed circuit board connections, elastomeric interconnects, tape-automated bonding (Tomita, 1989), and even chip-on-glass technology (Ishihara, 1989). Cost projections for these external-drive circuits range from about 40% of the direct material costs of display manufacturing (Mentley, 1989) to about 50% of the total system costs (Firester, unpublished).

Many developers have been pursuing the integration of this drive circuitry with the active matrix itself. The basic supporting argument is that, given yields adequate to fabricate an active matrix with 1 million perfect TFTs, several tens of thousands additional TFTs forming the drive circuitry will not substantially decrease the overall yields. Indeed with redundancy the yields can be enhanced. Nonetheless there is disagreement whether total system yields are enhanced (Mentley, 1989; Morozumi, 1989) or decreased (Ishihara, 1989) by the addition of integrated drive circuitry.

Perhaps the application for which integrated drivers will be most important is LCD projectors. Here the system cost advantages of small LC light valve size push designs to smaller and smaller pixel periodicities, which also strain available fine-pitch external interconnect technologies.

INVESTMENT ENVIRONMENT

The first active matrix products were introduced in 1980 by Seiko-Epson. These were very small portable personal television sets. The first was a "Dick Tracy" wristwatch monochrome, which was later followed by a 1.5-inch diagonal color TV. These gadgets were quite expensive and did not generate very large sales volumes; but they did point the way to future potential opportunities for larger sizes and lower costs. Although these products seemed to indicate a classic thrust of a non-television manufacturer into new markets (watches to television), it was recognized by the television producers as an opportunity, and they began major R&D efforts into active matrix technologies and announced pilot start-up plans. Not surprisingly, other non-television manufacturers became interested and entered the race. The chronology of these efforts is summarized in Table 5.1.

For perhaps a number of causes, the early-entry personal television products grew rapidly to about 1 million units per year and slowed. Prices were high for the active matrix products, and functionality was not commensurately high. The major producers were Seiko, Sharp, Matsushita, and Casio. Additionally, during this period the United States levied a dumping duty on TVs, and the major manufacturers stopped exporting TVs to the United States.

Table 5.1
Chronology of Efforts

<u>Company</u>	<u>Technology</u>	<u>R&D</u>	<u>Pilot</u>
Sharp	Amorphous Silicon TFT	1982	1985
Hitachi	Amorphous Silicon TFT	1983	1986
	Polysilicon TFT	1983	
Matsushita	Amorphous Silicon TFT	1983	1986
Seiko	Polysilicon TFT	1983	1984
	MIM	1985	1987
Mitsubishi	Amorphous Silicon TFT	1986	1990
Casio	Amorphous Silicon Diode Matrix	1987	1991
Hosiden	Amorphous Silicon TFT	1984	1986

Although significant advances were made in passive matrix displays, it was soon widely recognized that the laptop computer display market could be best served by active matrix LCDs. This recognition and the steady advances in the technology drove even higher investments into production facilities to serve the new markets for larger area displays. These investments and production capacities are shown in Table 5.2.

Today, Japan has established a technical environment that drives the current business environment for display technologies. The Japanese companies are making major efforts to bring up the yields in their amorphous silicon factories so as to realize as soon as possible the benefits of these major investments. Indeed, the manufacturers we visited clearly implied (and sometimes stated) that research in next-generation technologies such as low-temperature polysilicon was not being

Table 8.2
Business Strategies of Leaders

Company Strategy & Investment	'89-'98 Revenue (BY Estimate)	Production start
Sharp Major investments. Currently profitable in <5-inch TFTs. Overall company synergy is high - "LCD Sharp"	600	1990: 10" 1987: 3"
Toshiba Joint venture with IBM. Synergy with "Dynabook" product. LCD in key strategic position - "D (Display) Strategy."	50	1991
Seiko-Epson Leader of low cost MIM. TFT to be used in projectors. Considered "old establishment" in LCD industry. Polysilicon capability.	NA	1990
Hitachi Oriented toward high grade WS products. Steady investment at Mobarra; aim for early return	80	1990
Hosiden Firm ranks top in TFT. Crucial future issues are increasing investment and manpower. Mass production of 10-inch B/W and 5-inch Color TFT panels.	40	1990
Sanyo Electric Production of MIM and TFT. Company not in CRTs; LCD expectations are high.		
Matsushita Electric Industries Established LCD SUM. Current production of 1-inch viewfinders; 15,000 substrates/month.		
Sony Monthly production of 40 to 60,000 1-inch sheets. Will not enter 10-inch market but will concentrate on 1- and 3-inch projection. Polysilicon capability.		
NEC Mass production of 4- and 9-inch displays for TV and PC markets. Annual production of 20,000 sheets in 4Q90. Outside sales in 3 to 5 years time expected 1.2 million PCs.		
Kyocera Plans to enter TFT market. Mass production of STN.		

pursued as aggressively as it should be because the preponderance of the company's technical resources was immersed in the amorphous silicon production start-up.

As an example, Hitachi has concluded on economic grounds that major innovations in technology are required and that currently the market entry point for TFT Liquid Crystal Modules (LCMs) is in the high-performance high-price workstation rather than in moderate-performance personal computers (PCs). On our visit Hitachi personnel specifically indicated the need for polysilicon technology as a key but admitted that the company has only limited resources to advance this technology.

Hitachi indicated that they believe that revolutionary technology of the type being researched by the Giant Technology Corporation (GTC) is necessary for the growth of the flat-display industry, but that Japan has inadequate technical resources available. Hitachi representatives called for international cooperation and expressed the view that the application of innovative technologies developed by technologists from other than flat-display areas (such as the printing industry) would be the way to advance the technology. Hitachi pointed to the need for new technology to achieve the projections and potential of flat displays by drawing an analogy with production of cathode-ray tubes (CRTs) and other major technologies. The major thesis was that if flat displays are to compete with CRTs, the economic metrics of the flat-display production will have to be closer to those achieved by CRTs today.

Hitachi presented a sequence of 11 figures that capture the essential elements of the thesis:

Figure 5.3 shows the progress of displays in Japan. The key point was that they view 1995 as a turning point in the takeoff of the TFT LCD display technologies. However, as Figure 5.4 shows, key economic production metrics need significant improvement in flat displays. Specifically, (a) the ratio of facilities and R&D investment to sales is much too high at present when compared with the semiconductor industry, and (b) the investment efficiency or ratio of annual sales increase to investment increase for flat displays is much too low for flat displays versus CRTs, although it is comparable to semiconductors.

These issues are combined and incorporated in the historical perspective of price elasticity shown in Figure 5.5. The key point to be made here is that, if TFT LCMs are to compete, they must follow a similar elasticity curve, which will require dramatic improvements over the current state of the art. Figure 5.6 shows the projected volumes of Color Display Tubes (CDTs), Color Picture Tubes (CPTs), LCMs, and TFT LCMs up to the year 2000.

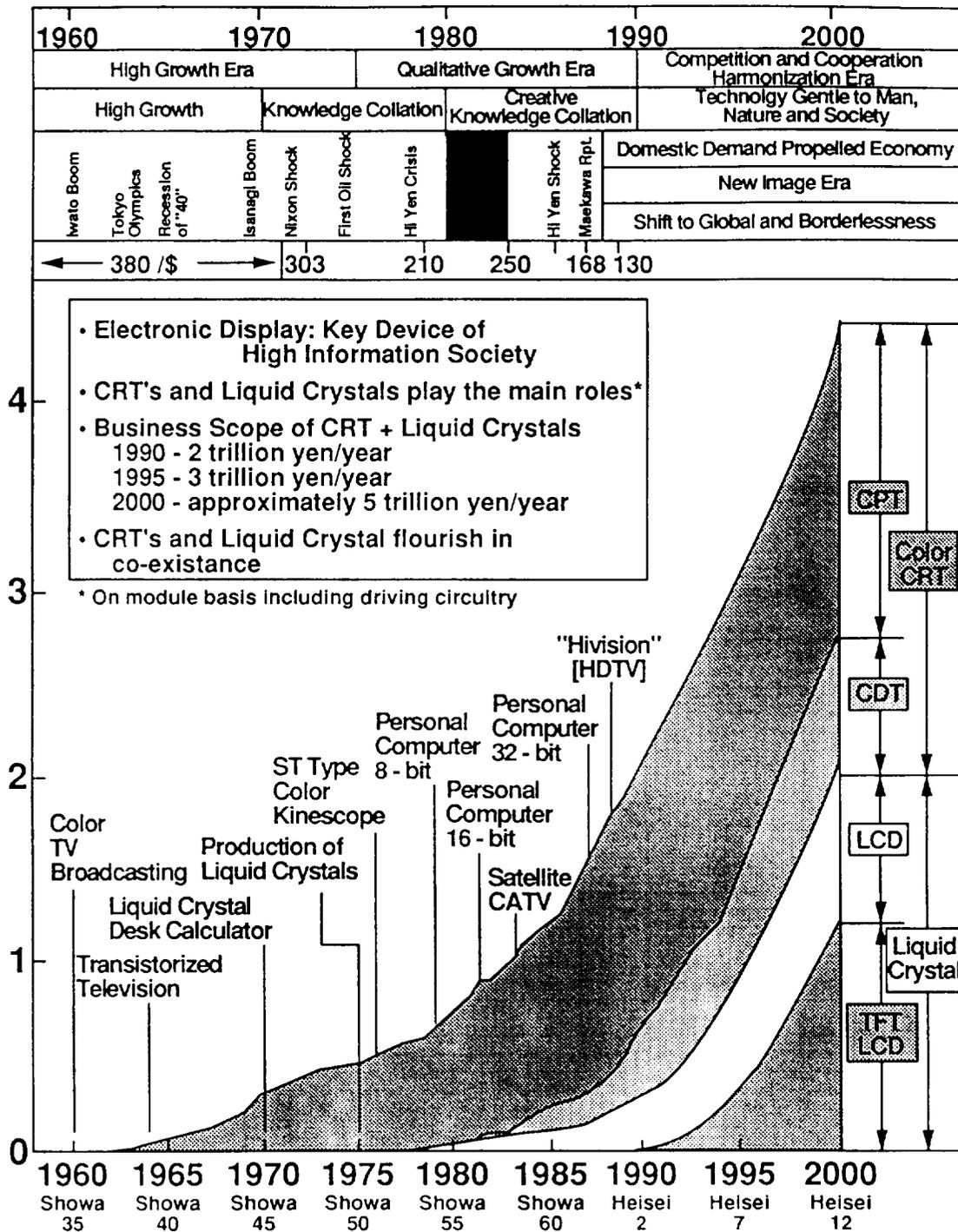
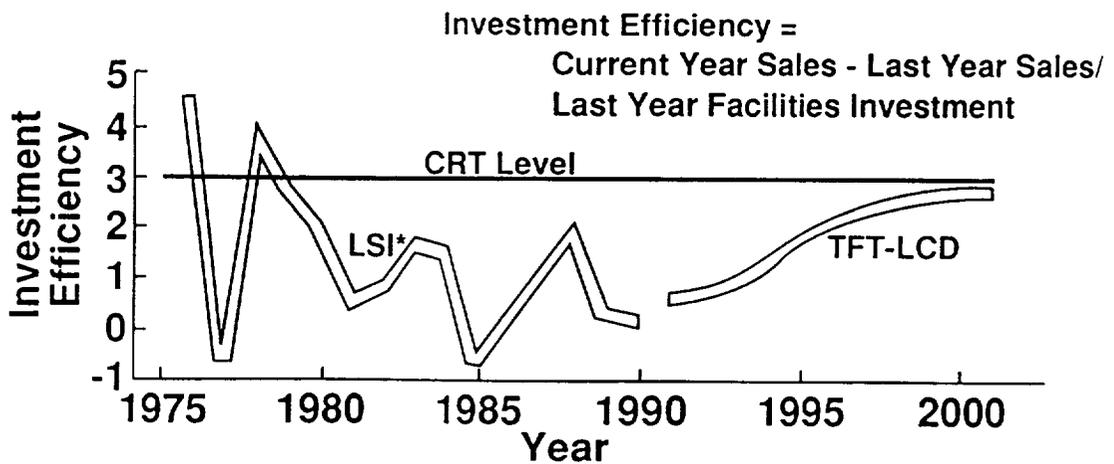
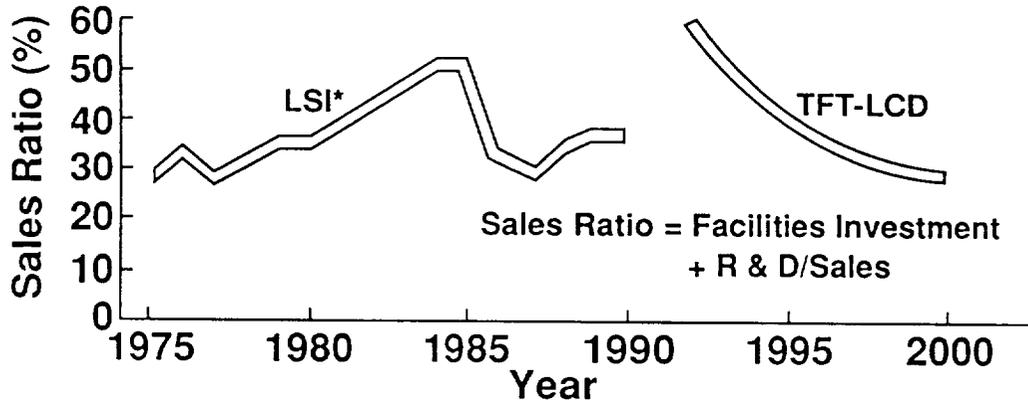
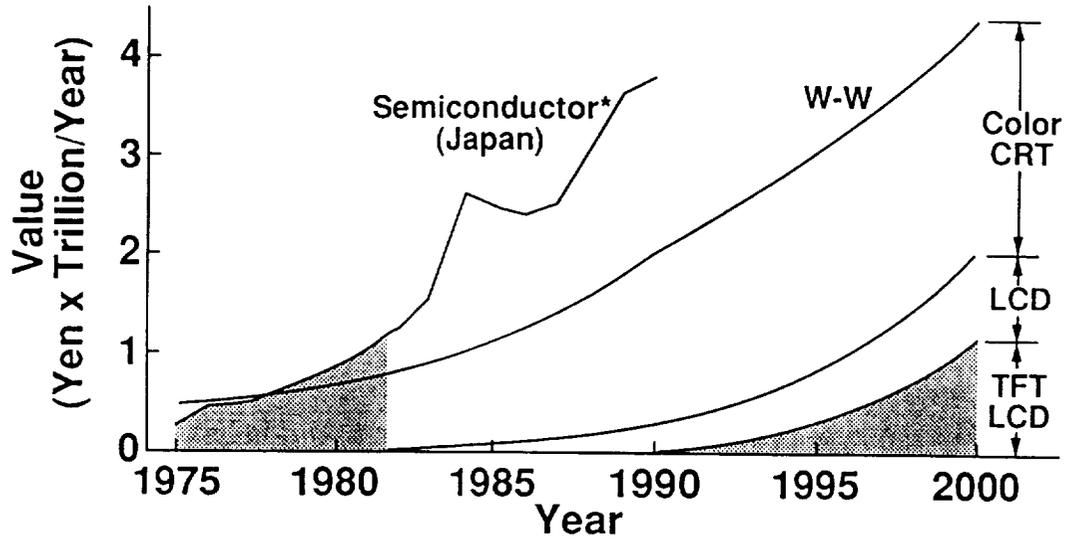


Figure 5.3. Progress of Displays in Japan



*Source: MITI Study of 12 Firms

Figure 5.4. Production and Investment Efficiency - Comparing Semiconductors & Displays

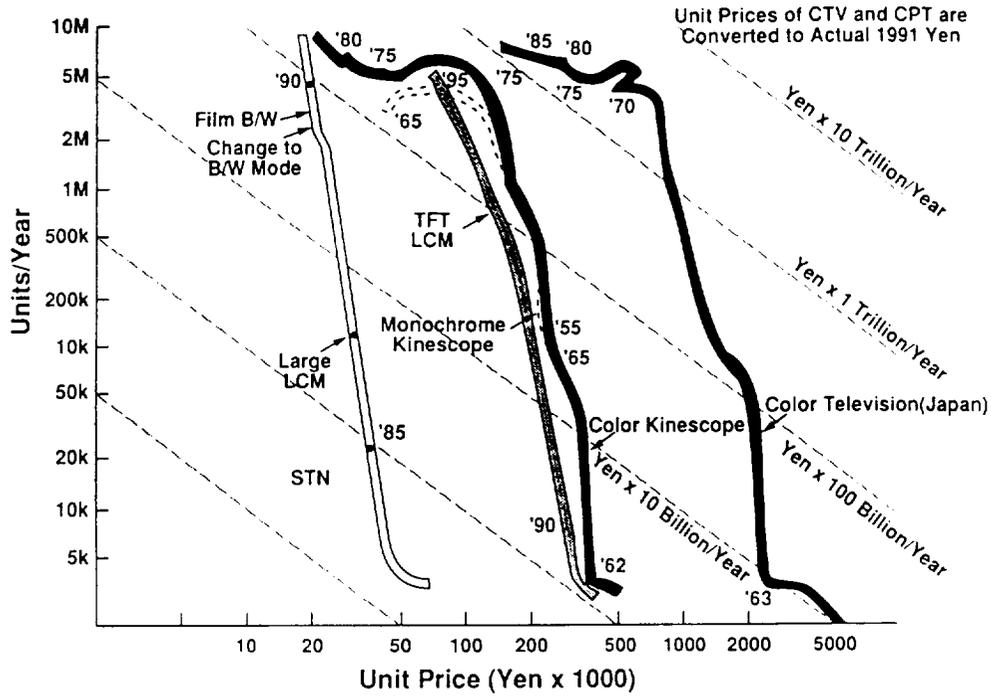


Figure 5.5. Price Elasticity of Color Kinescopes and Liquid Crystals

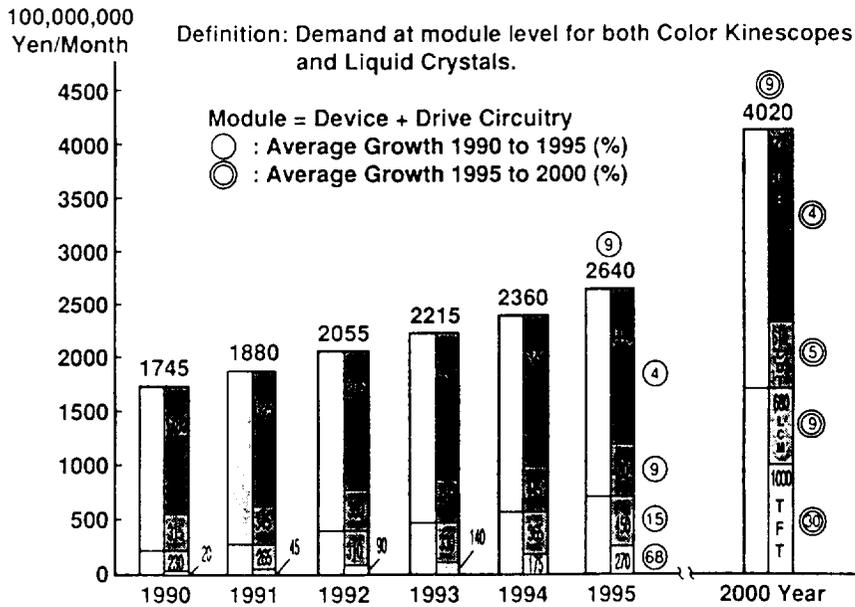


Figure 5.6. World Demand for Color Kinescopes - Liquid Crystal Modules

Figure 5.7 makes an interesting comparison of total lifetime power consumption for CRT and LCM displays. It indicates that, although the TFT LCM consumes less power than a CRT in operation, it requires much more power to produce, resulting in no substantive total lifetime power savings. Indeed, the shaded box and the arrows suggest that the power required to produce TFT LCMs is a significant impediment to the projected growth in production volume.

These arguments are further driven home by Figures 5.8-5.13. Figure 5.8 shows again the growth of the color television and personal computer workstation markets up to the year 2000. Figure 5.9 shows monthly growth in production of and revenue from TFT LCMs versus time, clearly showing the growth takeoff that must occur by 1995 if the predicted markets are to be achieved by the year 2000.

Figure 5.10 shows how significant penetration into the PC and workstation markets requires that the increased costs of TFT LCMs cannot be dramatically higher than color kinescopes (except for the high-performance, high-price markets, which are therefore Hitachi's current strategic interest). Figure 5.11 shows the learning curve improvements necessary to make the significant cost reductions and compares these learning curves with the historical learning curves of the CRT, making again the point that major technical innovations are necessary. Figures 5.12 and 5.13 summarize these requirements and their impact on the technology.

AMORPHOUS SILICON: THE DOMINANT ACTIVE MATRIX TECHNOLOGY

As we indicated earlier, amorphous silicon thin-film transistors are the dominant active matrix technology, and most of the production investments have been made in amorphous silicon. Some Japanese companies are pursuing other technologies. The two others worthy of note are MIM and polysilicon thin-film transistor active matrix technology. Specifically, Toshiba and Seiko-Epson are pursuing MIM technology for large display applications, and Seiko-Epson and Sony are pursuing polysilicon technology for small display applications. We will review the MIM technology here and will discuss the polysilicon technology later in this chapter.

Amorphous Silicon Active Matrix Technology

Amorphous silicon is the current technology of choice for most Japanese companies because it has adequate performance as an active matrix for current TV and all current computer applications; it is produced using a low-temperature process; and it is produced using a relatively simple process requiring equipment of modest cost.

Conditions:
Total Domestic Usage in Units: 50,000,000
Production in Units: 10,000,000 per year
Product Life: 5 Years
Hours in Use: 5 Hours per day

Increase in Home and Business Power Usage (10 Years)
($\Delta 2 + \Delta 3$)

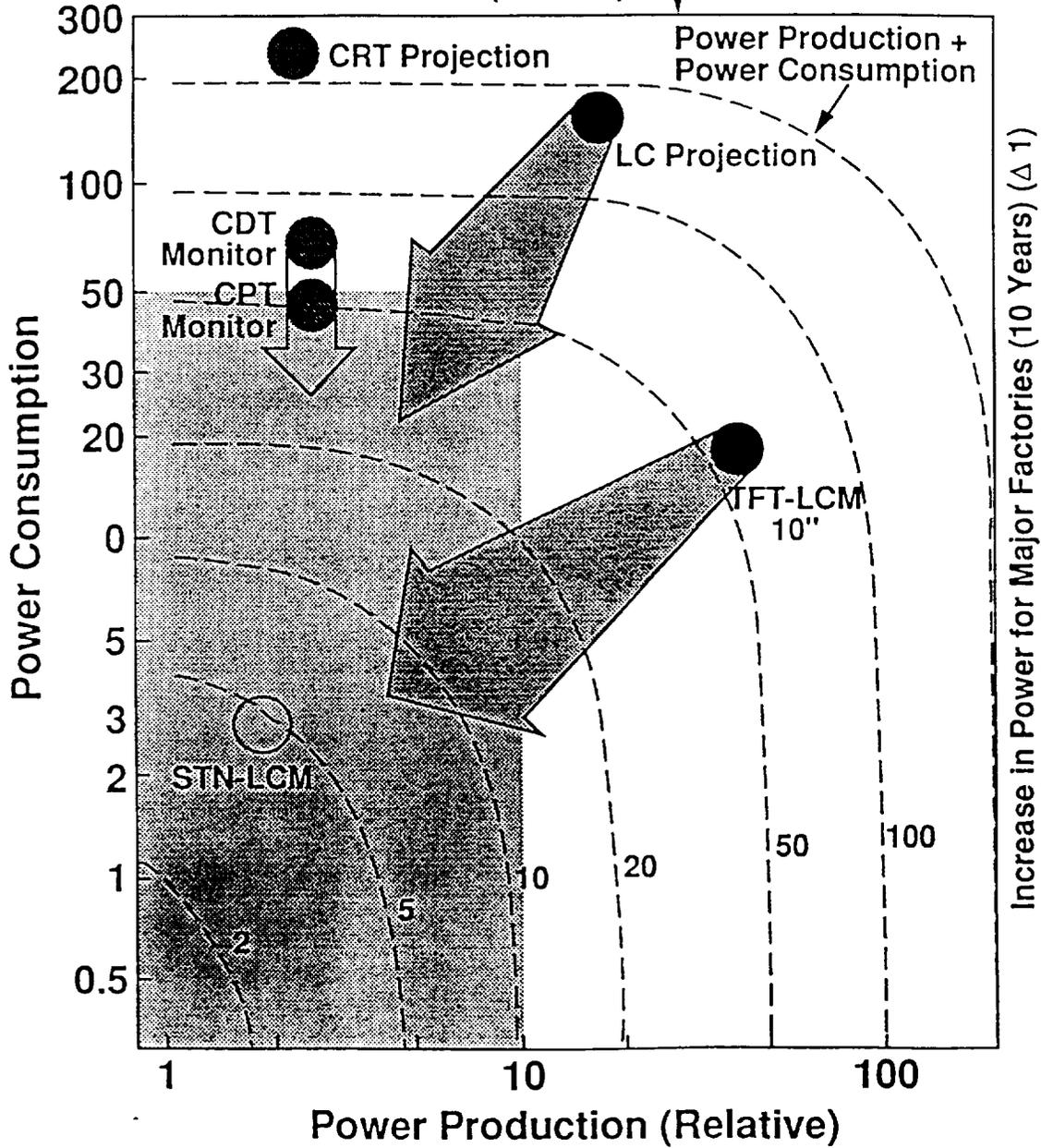


Figure 5.7. Power Consumption Reduction in Displays

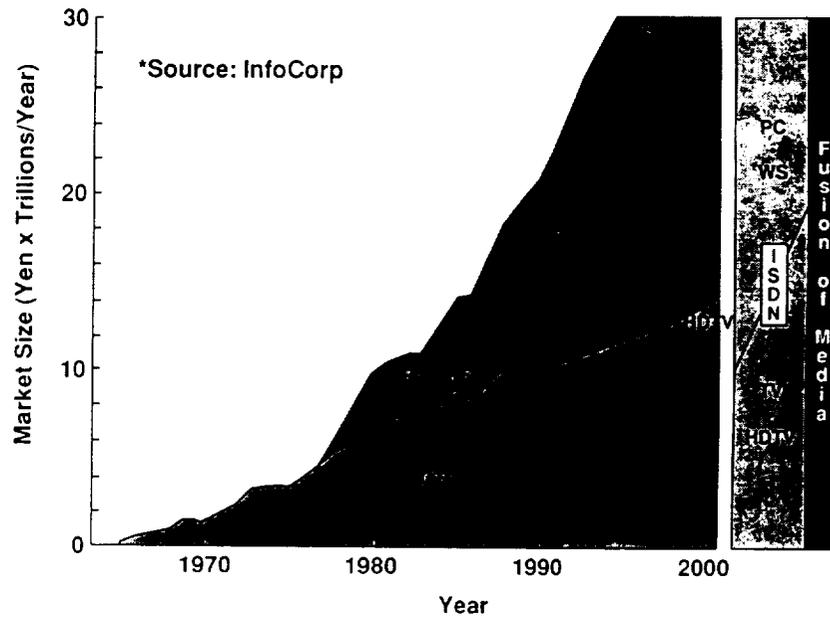


Figure 5.8. CTV - PC - WS Market

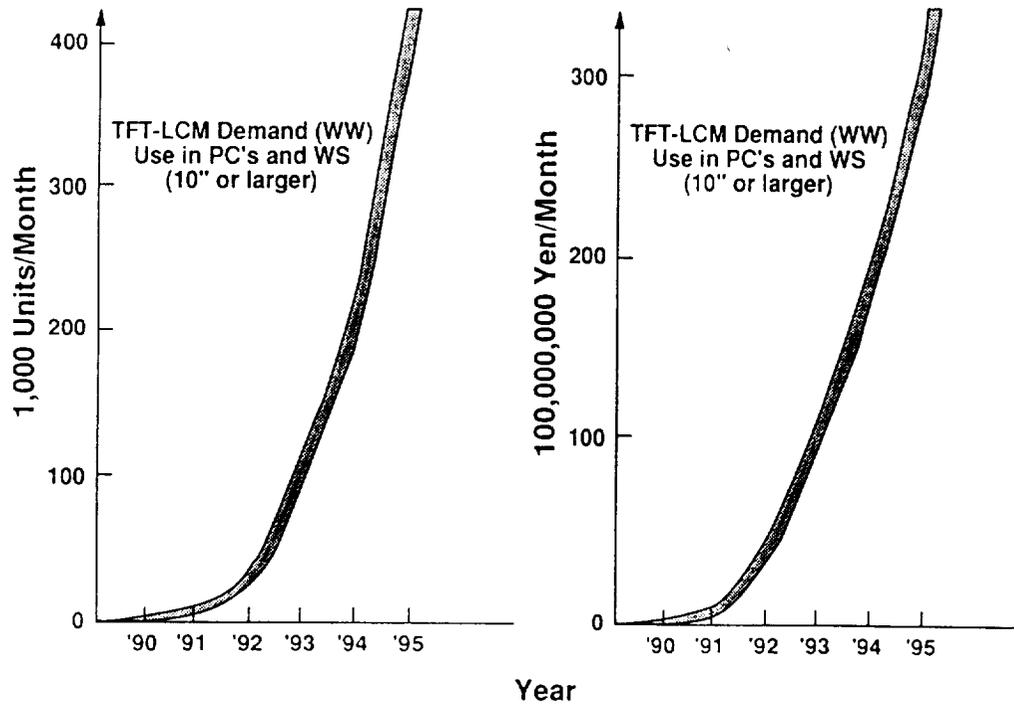


Figure 5.9. Probability of Adoption of TFT Liquid Crystals by the PC/WS Market

Class		PC			WS		
		A	B	C	A	B	C
P	Unit Price (Y x Million)	0.8~1.6	0.4~0.8	0.1~0.4	≥ 6	2~6	≤ 2
C	Degree of Resolution	High Resolution	Medium-High Res.	Medium Resolution	High Resolution		
W	Color	Color	Color/Mono	Color/Mono	Color	Color/Mono	Color/Mono
S	Size (")	10~12	≈10	≈10	≥14	12~14	10~12
	Market: (1,000 Units/Month)	400	1,100	1,500	12	28	280
Main Display		Color Kinescope		STN - Liquid Crystal	Color Kinescope		
TFT Adoption Probability	Main Display / Cost Multiple Ratio	X1.5	50%	1.5	80	80	60
		X2	30	20	60	65	40
		X2.5	20	6	50	50	30
		X3	13	3	45	45	18
		X3.5	10	1	40	40	12
		X4	7	0.5	35	35	7
		X5	4	0.05	30	25	3
		X10	0.2	—	15	7	0.2

* Source: InfoCorp

Figure 5.10. Probability of Adoption of TFT Liquid Crystals by the 1995 PC/WS Market

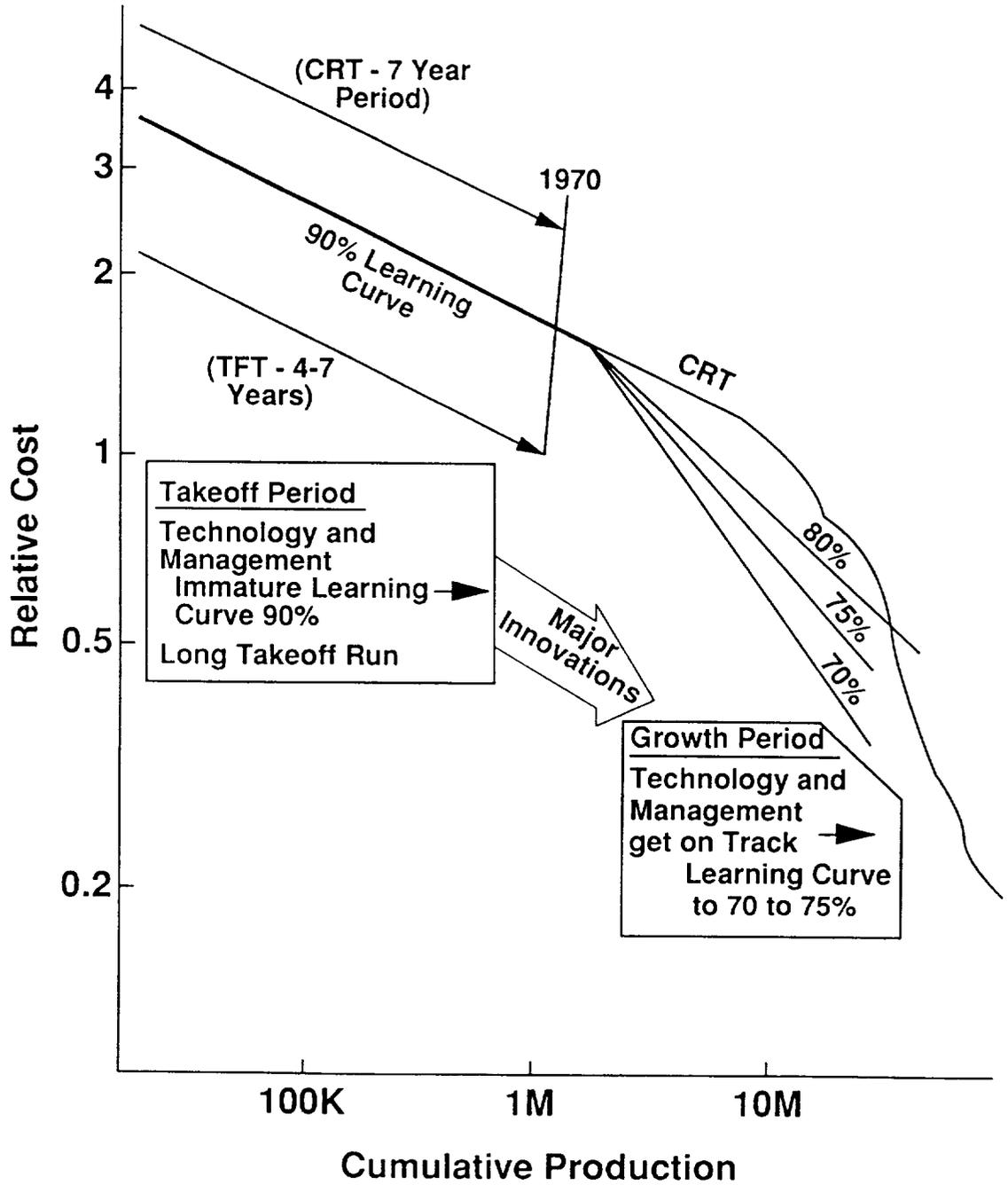


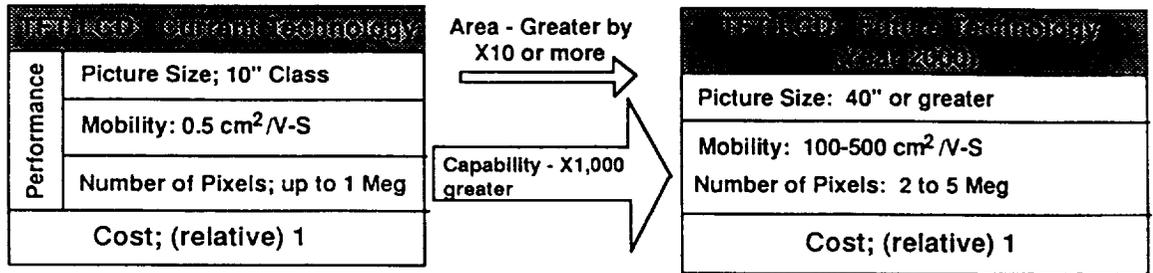
Figure 5.11. Adoption Probability of TFT Liquid Crystals by PC/WS Market

		TFT-Color LCD (1990)	➔	TFT-Color LCD (1995 Target)	STN-LCD	Color CRT
Indirect Cost	Facilities Investment Efficiency	Less Than 1	➔	1.5 - 2.5	4	3 or More
	Annual Sales/Facilities Investment	<ul style="list-style-type: none"> • Major Improvement in Throughput • Innovations in Methodology, Design and Processes 				
	Days in Production	Several Weeks	➔	Several Days	2 - 3 Days	1 Day
	R & D	<ul style="list-style-type: none"> • From Total Reliance on LSI Type Processing, Conversion to Processes Temperset with CRT Type Processing 				
	Ratio to Sales	Tens of %	➔	Approx. 15%	5 - 10%	Approx. 10%
	Overall (Management - Technology)	<ul style="list-style-type: none"> • R/D Structure in Depth Progressing in Same Time Frame as Third Generation • Joint Structures with Different Business Lines 				
		<ul style="list-style-type: none"> • Insufficiency of Technological Creativity • Technological Accumulation • Cost/Effect Imbalance 	➔	<ul style="list-style-type: none"> • Founding of Harmonious Giant Electronics' Technological Structure 		<ul style="list-style-type: none"> • Strength of Fundamental Lineage • Power of 40 Years' Experience

Figure 5.12. Cost Comparison of Color Kinescopes and Liquid Crystal (Indirect Cost)

Example of Requirements: Large Picture, High Detail, Low Power, Space Saving Flat Panel Display.
Candidates: In addition to CRT technology and Liquid Crystal technology, new technologies such as Plasma and EL are candidates.
Key Factor: Appearance of New Methods, New Materials and New Processes are the new factors.

1. Examples of Required Cost - Performance Levels



Both CRTs and MOS memories have achieved improvements of three orders of magnitude or higher from their initial periods.

2. Key to Realization

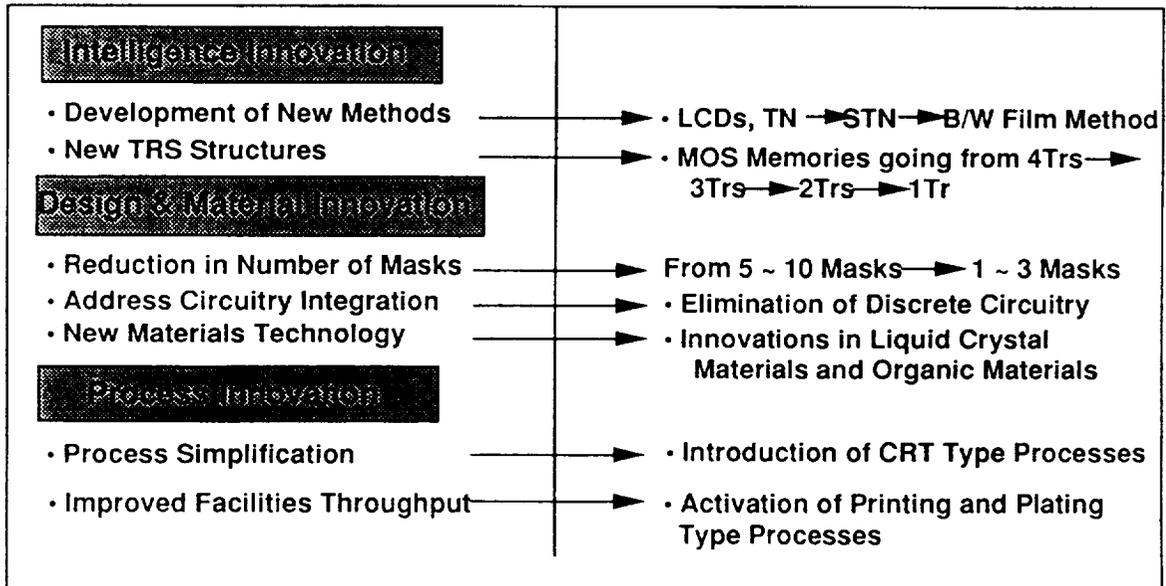


Figure 5.13. Display of the 21st Century

A-Si Process

The amorphous silicon thin-film transistor fabrication process is extremely simple. It can require as few as two mask steps, although most processes require about five mask levels. Figure 5.14 shows diagrammatically how amorphous silicon thin-film transistors are fabricated.

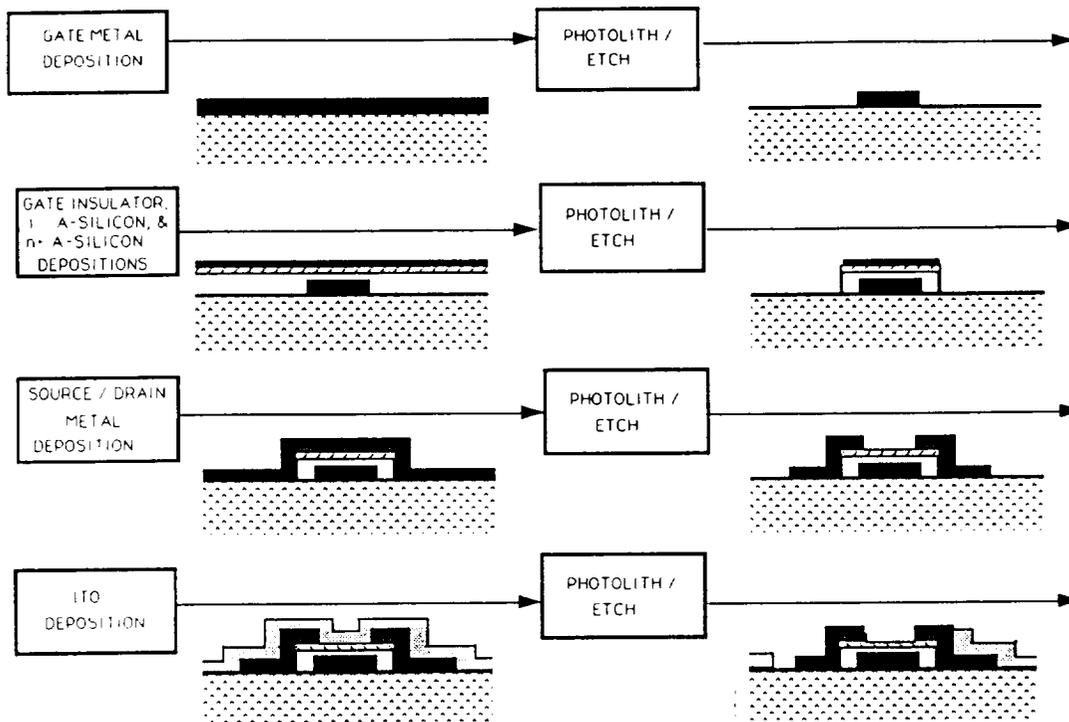


Figure 5.14. Amorphous Silicon Active Matrix Fabrication Process

As can be seen, most of the processes are readily scaled to large areas. The Plasma Enhanced Chemical Vapor Deposition (PECVD) process has been developed in the production of the amorphous silicon solar cells used in calculators and remote power sources. The large-area metal depositions have been developed through sputtering of high-quality coatings for CD discs and magnetic hard discs. Wet etching is a mature process, but specialized photolithography has been developed specifically for AMLCDs by experienced Very Large Scale Integration (VLSI) equipment manufacturers.

A-Si Recent Technical Achievements

One of the problems common to TFT active matrices relates to the gate delays caused by the select line resistivity. These lines form resistance-capacitance transmission lines that delay and distort the gate pulses. These effects limit the ultimate size of an active matrix display. Kato et al. discussed this relationship, as depicted graphically in Figure 5.15. Typically, a-Si TFT fabrication processes have used high-resistivity thin refractory metals, which have exacerbated the resistivity problem. To demonstrate larger area displays, new metallization systems have been developed. These have included a number of bimetal systems, such as Mo-Ta (Dohjo, 1988; Moriyama, 1989; Ichikawa, 1989), W-Ta (*Japan Display Digest*, 1989), Ta-Al-Ta (Katayama, 1989), Cr-Al (Moriyama, 1990) and Ta-Cu-Ta (Ikeda, 1989).

Advances pertaining to commercialization are frequently not published. Critical advances relate to product/process yields. At this stage in their development, a-Si device yields are low enough that developers are exploring techniques for redundancy. Examples of these have been published by Nippon Telephone and Telegraph (NTT) (Nakajima, 1989) and Seiko-Epson (Matsueda, 1989). Other yield-enhancing techniques include isolation of conducting layers by insulators (Moriyama, 1989) and the use of triple-stacked insulators (Ichikawa, 1989) of TaO_x/SiO_x/SiN_x.

NTT sought a commercial partner to co-develop two 15-inch diagonal flat-panel displays that could be used as a component of a high-resolution teleconferencing system with graphics and realistic video capabilities. NTT provided three specific technologies: redundancy technology, high-speed driver technology, and low-resistance bus-line technology.

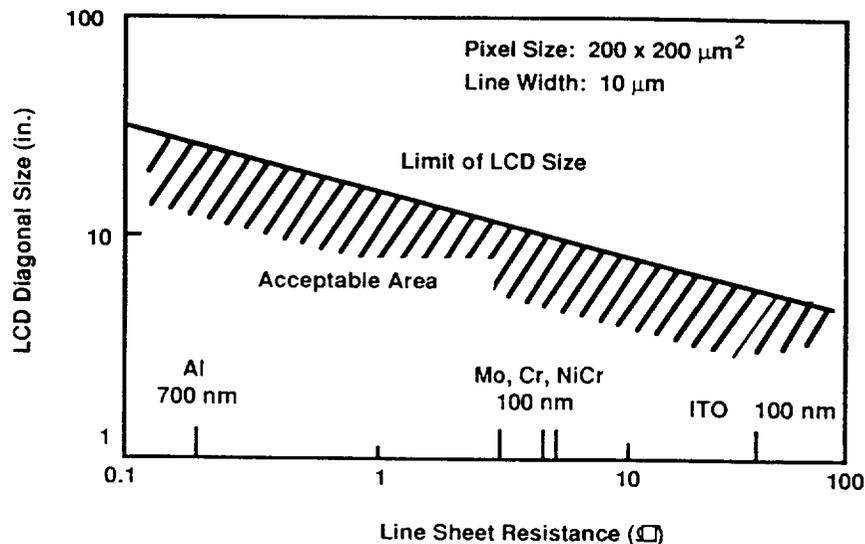


Figure 5.15. Size Limitation of an Active Matrix Display

The display has a 4-bit gray scale and was developed in two versions. One, a VGA version, has 1920 x 480 TFT subpixels arranged in a stripe configuration for 640 x 480 color pixels. The second, a high-resolution version, has 1920 x 1600 TFT subpixels arranged into triads for 1280 x 800 color pixels. There are several driving modes for this display: 1120 x 750 color pixels at 40 frames per second interlaced; 640 x 400 color pixels at 56.4 frames per second progressive scan; and 1024 x 760 pixels (reference NTT trip report in Appendix B).

One significant advance demonstrated by Hosiden is the amorphous silicon active matrix implementation of 10-inch diagonal full-color active matrix LCD using a halftone-gray scale method. This technique results in dramatic improvements in viewing angle by replacing each pixel with a number of subpixels. At any particular analog voltage, some of the subpixels may be operated in saturation thereby providing the wide viewing angle properties of a binary display in its contribution to the pixel transmission. As an example, the vertical viewing angle for a conventional display at 50% graylevel is -40° , $+12^\circ$ while the halftone gray scale is -65° , $+30^\circ$.

Metal-Insulator-Metal Active Matrix Technology

Companies continue to develop MIM technology because it has adequate performance as an active matrix for personal (small-size) TV and monochrome and limited color computer applications; it is produced using a very-low-temperature process; and it can be produced using a very simple process requiring mostly low-cost equipment.

MIM Performance. The basic issue with MIM active matrix technology is the limited nonlinearity of the basic MIM devices. This problem is compounded by a strong temperature sensitivity. Furthermore the basic problem with all series diode-type active matrices is that device nonuniformities are directly translated into visual nonuniformities in gray scale. Most display manufacturers do not believe that MIMs offer sufficient cost advantages to offset their performance disadvantages. Toshiba and Seiko-Epson are the exceptions.

Toshiba has developed and demonstrated a commercial monochrome display using the MIM technology. Toshiba refers to this as TFD (thin-film diode) technology. The product, announced in 1991, is a 12-inch diagonal with 1052 x 900 pixels. It is expected that this product will be used by Toshiba in a SPARC workstation product and by Sun Microsystems.

Seiko-Epson currently markets 3- to 4-inch color TVs using MIM technology and expects to expand its production capacity to produce 10-inch diagonal and larger MIMs for the computer markets. Nonetheless, Seiko-Epson representatives expressed the need for continuing research in MIMs to extend the operating temperature range and increase the intrinsic nonlinearity, which is necessary for

increasing the resolution gray scale capability of MIM displays. Current Seiko-Epson products are typically 3.5 inches diagonal with 220 x 300 pixels, stripe filter, and 32 levels of gray scale.

MIM Process Temperature Impact. MIM process temperatures are below 300°C. Thus MIMs can be fabricated on very low-cost glass substrates such as soda lime glasses or Nippon Electric Glass Company BLC glass. These glasses are potentially an order of magnitude less costly than the commonly used Corning 7059 glass.

MIM Process. The MIM fabrication process is extremely simple, requiring only two mask steps and very simple photolithography. Figure 5.16 shows diagrammatically how MIMs are fabricated.

Toshiba is aggressively working to develop very low-cost, high-throughput MIM production technology. As an example, it is using a proximity printer and soda lime glass dip-coated in SiO₂.

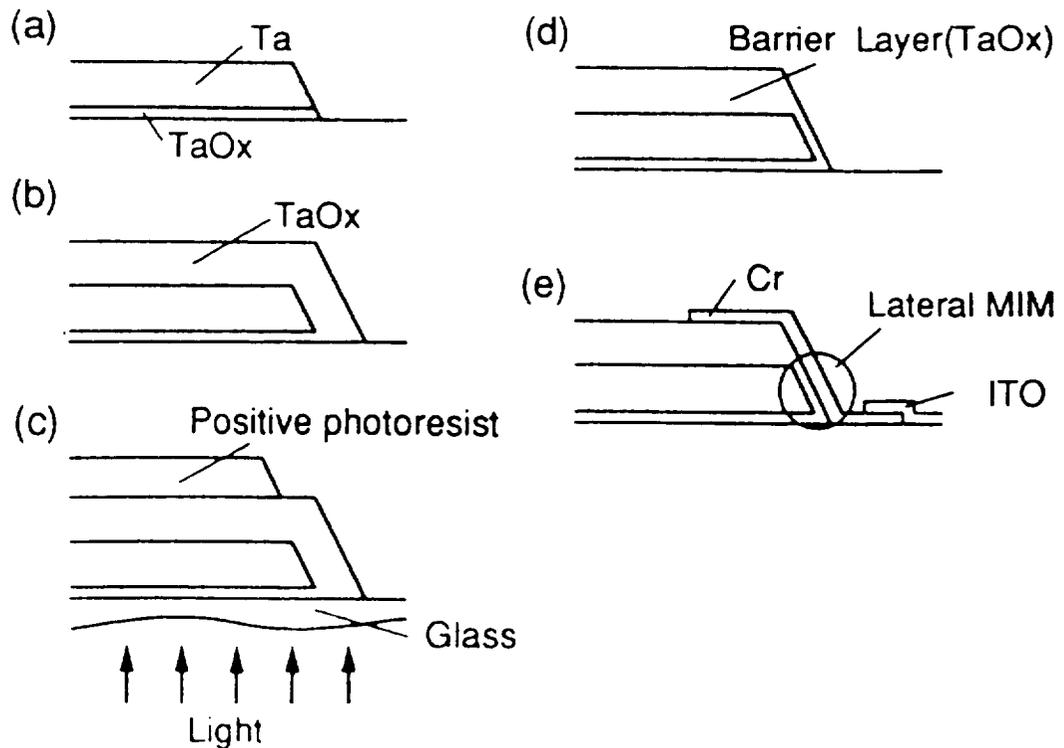


Figure 5.16. MIM Fabrication

POLYSILICON: THE SUCCESSOR TECHNOLOGY

R&D on and production interest in polysilicon technology for active matrix LCDs are growing. The primary attraction is that "the cost of the external VLSI drive electronics is the largest component cost in an LCD system....If it becomes practicable, the p-Si TFT will be a promising display device, as its driver circuits can be formed at the same time on the same glass substrate as the panel" (Minami, 1991).

P-Si is perceived to be able to provide higher aperture ratio displays at high pixel densities (Matsueda, 1991). Additionally, for high pixel densities the interconnect problem becomes intractable. Tape Automated Bonding (TAB) is capable of about 100 μm pitch at best. Thus p-Si is the technology of choice on both counts for projection technology. What primarily drives p-Si R&D is the potential for cost reduction and improved reliability by integrating the display drive circuitry onto the active matrix substrate and eliminating the huge number of interconnections to external VLSI drive circuitry.

Seiko-Epson, the industry pioneer, continues to perform R&D and production. The motivation is primarily to use the technology for small display products such as camcorder viewfinders and projection light valves. Sony recently announced its entry into the production of p-Si devices for viewfinders. Viewfinder components were demonstrated at Japan Electronics Show '91. Indeed, the two Japanese R&D consortia, GTC and HDTEC, have focused on p-Si in developing, respectively, the next generation direct-view HDTV-on-the-wall and projection HDTV. Hitachi management has identified 1995 as the point of dramatic volume expansion and believes that if this is to occur, p-Si technology, with its integrated drive technology, will be necessary.

P-Si Process

The polysilicon active matrix fabrication process is relatively simple. It minimally requires about five mask steps. Figure 5.17 shows diagrammatically how polysilicon thin-film transistors are fabricated. Most of the processes are very similar to bulk silicon VLSI processes. Herein lie both an advantage and a disadvantage. The advantage is that tremendous experience exists in these process technologies, albeit at much smaller substrate sizes. The disadvantage is that many of these processes require high temperatures and are potentially expensive to scale up in area or difficult to scale down in temperature.

P-Si Recent Technical Achievements

Seiko-Epson has demonstrated a prototype 9.5-inch diagonal p-Si active matrix display. This is perhaps the largest polysilicon display prototype to be demonstrated

to date. This display was fabricated using a process with a maximum temperature of 600°C. Using thin devices, about 25 nm thick, ON/OFF ratios of greater than 1E7 were demonstrated (Little, 1991).

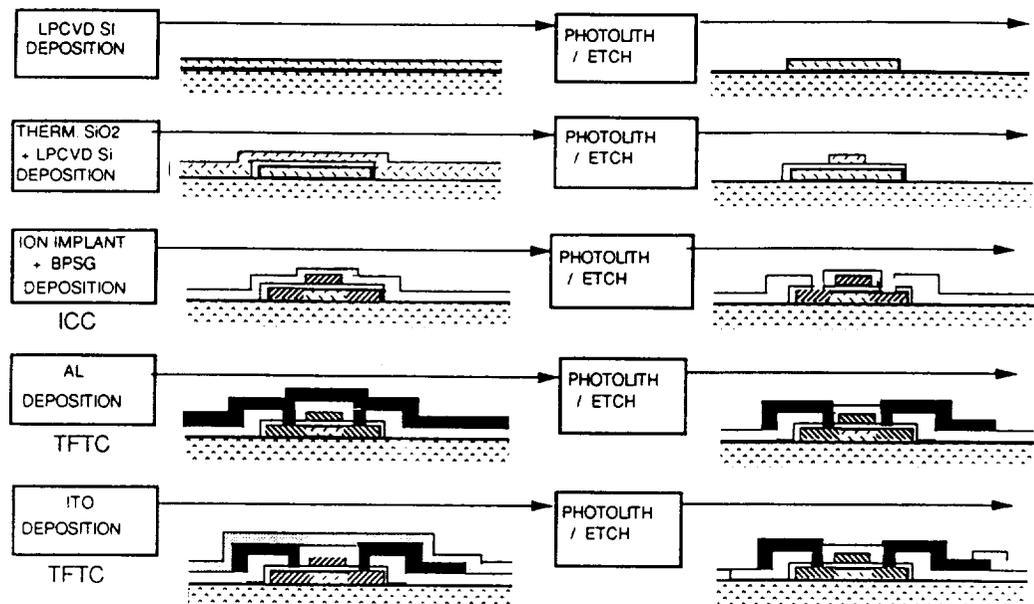


Figure 5.17. Poly-Silicon Active Matrix Fabrication Process

Researchers at Asahi Glass Research Center demonstrated comparable ON/OFF ratios using a process with a maximum temperature of 450°C. At this temperature many available hard glasses could be used as display substrates. These researchers did this work on Asahi non-alkaline glass (Endo, 1991). Much of this work continued their earlier work in which Asahi described a self-aligned 450°C process using a non-mass separated ion implantation (Yuki, 1990).

Researchers at Sony demonstrated 44% aperture ratio viewfinder displays with 42 μm x 48 μm pixels using their Superthin Film Transistor (SFT) polysilicon technology. SFTs with lightly doped drains were specifically developed to reduce leakage in the pixel transistors. Both horizontal and vertical drive circuitry was integrated onto the display using CMOS SFTs (Hayashi, 1990).

One of the issues with polysilicon is that leakage currents tend to be high. Researchers at NTT proposed and demonstrated a new type of TFT which they term

a Field Induction Drain (FID) TFT. This TFT has lower off current than a conventional one; indeed they have demonstrated an improvement of about 100 (Tanaka, 1991).

COMMERCIAL PRODUCTS AND PROTOTYPES

Tables 5.3, 5.4, and 5.5 list representative products by the major manufacturers in the various sizes--largest, medium, projection light valves, and viewfinders.

CONCLUSIONS

The main thrust in active matrix technology is directed towards establishing cost-effective manufacturing of amorphous silicon AMLCDs. Substantial capital investments have been made by many companies in factories for laptop computer displays. These factories are not yet running at capacities probably because the yields are too low compared with prices that the high volume market will support.

In this environment, technical resources are committed to fixing factory and product issues and are not able to concentrate on the next generation of display research. The results of researchers' labors tend to be closely held and only bits and pieces are published and openly discussed.

Specific technical achievements have included lower resistance gate metallization systems, multiple/layer gate insulators and superb prototype displays pushing out both the resolution (1920 x 1600 TFTs) and size (15-inch) boundaries.

Seiko-Epson and Toshiba continue to develop MIM technologies and have demonstrated products and prototypes. Nonetheless, MIMs are expected to only serve limited applications in which cost is more severely constrained than performance.

Research is continuing on low temperature polysilicon because it is generally perceived to be a promising technology. Nonetheless, although there has been progress and consistent achievements, no technical breakthroughs have appeared, probably because the Japanese level of effort is much reduced (and is applied to amorphous silicon factory startup problems). The market niche that drives polysilicon currently is for viewfinders and projection light valves, both of which are low volumes in terms of area production. In these applications, the ability to integrate the drive electronics onto the AM substrate provides a significant, and at times enabling, advantage.

Table 8.3
A-Si Displays

<u>Company</u>	<u>Size/Resolution</u>	<u>Product/Prototype</u>
Hosiden	15-inch, 1280 x 800, color	AV, prototype
	10-inch, 1024 x 1024, color	OA, avionic wide viewing-angle prototype
Sharp	14-inch, 16.5-inch	
	10-inch, 11.8-inch	Laptop VGA & XGA computer
	8.4-inch	Notebook computer
	8.6-inch	Portrait TV
	5.5-inch	HDTV projector LV
	5.7-inch, 4-inch, 3-inch	Personal TV
Hitachi	10-inch, 640 x 480, color	Laptop computer product
	10-inch, 1120 x 780, color	Prototype
Toshiba-IBM (DTI)	10.4-inch, 640 x 480, color	Laptop computer product
Matsushita	15-inch, 1152 x 900, color	Prototype
	10-inch	Laptop product

Table 8.4
MIM Displays

<u>Company</u>	<u>Size/Resolution</u>	<u>Product/Prototype</u>
Toshiba	12-inch, 1052 x 900, B/W	SPARC product
Seiko	4-inch, 300 x 220, color	Personal TV

Table 5.5
P-Si Displays

<u>Company</u>	<u>Size/Resolution</u>	<u>Product/Prototype</u>
Seiko	0.7-inch, 320 x 220 1.32-inch, 480 x 440	Viewfinder (OEM) Projector Model VPJ-2000
Sony	0.7-inch, 350 x 220 1-inch	Viewfinder Product Viewfinder Projector Product
Matsushita	0.7-inch, 320 x 232	Viewfinder Prototype

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CHAPTER 6

PROJECTION DISPLAYS

William E. Glenn

INTRODUCTION

In Japan much of the new display development has been motivated by the high-definition television (HDTV) or "hi-vision" market, which the Japanese see as the next big advance in television. It has been recognized that high-definition images at normal home viewing distances should be at least 36 inches diagonal, and preferably 50 - 60 inches. In these sizes the direct-view shadow-mask tube is quite impractical. It is felt that unless an economical thin display in the 50-inch range can be developed, the future of consumer HDTV will be quite limited. At this time the only feasible options seem to be either direct-view large panels--such as plasma display panels (PDPs) or active matrix liquid crystal display (AMLCD) panels--or projectors. Even though there is an effort by the Giant Technology Corporation (GTC), partially under government sponsorship, to develop economical large AMLCD panels, there is considerable skepticism in the industry that the effort will be economically successful. PDP panels appear likely to be less costly, but in experimental displays they have been marginal in brightness, contrast, and uniformity.

In the short term, only projectors seem to have the cost and performance characteristics for consumer HDTV displays. For large-screen displays, cathode-ray tube (CRT) projectors with good performance have been produced. However, the AMLCD light-valve projector is rapidly surpassing the CRT projector as a technology that can meet the cost and performance objectives.

AMLCD panels are under very active development, primarily for color computer displays. This same technology is suitable for the light modulator panel in light-valve

projectors. In fact, the small panels used in projectors are cheaper and easier to produce than direct-view panels. To produce color, direct-view panels need three times as many addressable subpixels as there are pixels in the image. A projector uses three small panels but needs only one addressable pixel per displayed pixel in each panel. Consequently, the yield requirements for high-resolution panels are far less severe for projectors than for direct-view color panels. Furthermore, on a substrate that will produce only one 14-inch direct-view panel, about nine projector panels can be produced--enough for three projectors. On a substrate that will produce one 44-inch panel, enough projector panels can be produced to make 30 projectors.

Since the light-valve projectors are single-lens devices with very accurately produced image plane geometry, the convergence problems that have plagued CRT projectors do not occur.

It is clear that while large hang-on-the-wall panels are a long-range goal for satisfying the display needs for HDTV, the light-valve projector is the prime candidate for the short-range solution. Sanyo, Seiko-Epson, and Sharp have invested heavily in the development of AMLCD projectors. HDTEC, a consortium that is partially supported by the MPT in Japan, is developing a consumer back-projection HDTV display using AMLCD light valves.

COMPARISON OF JAPANESE AND U.S. DISPLAY RESEARCH

Over the past 40 years, the United States has been a leader in basic research in projection displays. In the 1950s and '60s, in the basic technology in projection CRTs and light-valve projectors (the GE Talaria projector), U.S. research dominated the field (Glenn, 1970). Currently, university laboratories in both countries are doing quite competitive basic work. In both the United States and Japan, a large part of the basic research is funded by some governmental agency. During the study there was a discussion between Dr. Doane, a panel member, and Dr. Uchida, a Japanese professor, both of whom headed liquid crystal research laboratories. They estimated that the number of expert researchers in liquid crystal research in both countries was about the same.

The development of reflective, optically addressed projectors by Hughes (Sterling et al., 1990) using twisted nematic (TN) liquid crystal materials has its counterpart in the NHK (Takizawa et al., 1991) effort to develop an optically addressed polymer-dispersed liquid crystal projector. The research on on-panel polysilicon drivers for projection at Sarnoff Labs (Lee, 1990) and Xerox (Thompson) has its counterpart at Seiko-Epson (Aruga et al., 1987) and several other Japanese companies. Basic research in efficient solid-state lasers at the three primary colors that could make laser scanner projectors practical has a comparable level of effort in both countries.

We found no effort in Japan that corresponded to the deflected-mirror arrays under development by TI (Hornbeck, 1989).

The development of a metal halide arc with high brightness and a 2000-hour life suitable for light-valve projector applications has been successfully accomplished in both Japan and Europe. In the United States, metal halide arcs were developed many years ago with higher brightness and a 75-hour life or lower brightness and a 15,000-hour life, but none that meets the requirements of consumer TV light valves. Xenon arcs for light-valve projectors are being manufactured in the United States by GE and Optical Radiation (Kramer, 1988).

Table 6.1 provides a partial list of the laboratories in both countries and the technologies they are developing that apply to projectors.

TECHNICAL EVALUATION OF WORK

Even though research in CRT projectors continues, the major effort seems to have shifted to AMLCD light-valve projectors. These projectors now provide images with excellent quality and have a number of cost and performance advantages. Since the panels used are geometrically very accurate and a single projection lens is used, they have no registration problems. The projectors can be moved from place to place and can be simply focused like slide projectors. Their size is relatively small. They require no high-voltage power. Their contrast, color rendition, uniformity, resolution, and motion rendition are all excellent.

AMLCD projectors have a number of problems that affect cost and performance. This section discusses how Japanese companies are addressing these problems.

Active Matrix and Array Drivers

Most of the designs to date use amorphous silicon thin-film transistor (TFT) elements at each pixel with silicon chip drivers external to the panel. Since a-Si is light-sensitive, it must be well shielded from the high-flux-density light passing through the panel. The technique for connecting the chip and the panel can be a cost and yield problem. Consequently most companies are experimenting with polysilicon row and column drivers on the panel. Polysilicon has a high enough mobility to provide adequate rise times to switch the rows and columns. For high-definition column drivers, the switching time is generally not fast enough. Consequently, the line is divided into roughly six segments, and six columns are driven in parallel at a lower clock rate.

Table 6.1
Basic Research on Projector Technology

Technology	Japanese Laboratory	U.S. Laboratory
Liquid Crystal Materials	Tohoku University Merk (German owned) Chiso Dainippon Ink & Chem.	Kent State University
Projector panels with polysilicon drivers	Seiko Epson Sharp Research	Sarnoff Labs Xerox Labs
Laser scanners		Harris Naval Ocean Systems Center
Solid State Lasers	Sony Sanyo	Amoco Laser Univ. Central Florida Univ Colorado
Metal Halide Arc & Xenon	?	G.E. Optical Radiation
Deflected-Mirror Light-valve		Texas Instruments
Light-Valve Optics	HDTEC NHK Sharp NEC (other)	Florida Atlantic Univ. CREOL (UCF) MCC Eastman Kodak Xerox Labs

The effort at Seiko-Epson (Thompson) uses polysilicon (p-Si) for both the drivers and the pixel TFT. Since polysilicon TFTs are not light-sensitive, they do not need a light shield. In the Sharp (Katoyama, 1988) effort, two redundant pixel TFTs, row lines, and column lines are used to improve yield. A self-alignment structure is used to improve yield by preventing misregistration of successive masks. This all-polysilicon technique uses quartz as a high-temperature substrate. Research is attempting to produce an all-polysilicon structure on a high-temperature glass substrate.

NEC is working on a hybrid structure (Sakamoto et al., 1991) in which a-Si is used for the pixel TFT and laser recrystallized polysilicon is used for the row and column drivers on the same glass substrate.

Table 6.2 shows the techniques currently in use. Most companies are working on all-polysilicon panels, with drivers on the panels, on a high-temperature glass substrate for projectors. NHK is using an optically addressed reflective light-valve projector (Takizawa, 1991), a scheme similar to the one used by Hughes in the United States (Sterling, 1990). It consists of a sandwich with a photoconductor, an insulating reflecting surface, and a liquid crystal. Hughes uses a TN liquid crystal, and NHK uses a polymer-dispersed liquid crystal (PDLC).

Table 6.2
Driver Technology for LCD Panels

Company	Row & Column drivers	Pixel TFT	Alternate addressing
Sharp	Silicon	A-Si	
Sanyo	Silicon	A-Si	
NEC	Silicon or polysilicon	A-Si	
Hitachi			Optical
NHK			Optical
Seiko-Epson	Polysilicon	Polysilicon	

Liquid Crystal

Most projectors use TN liquid crystals for projector panels. In a projector the reduction in contrast for TN panels at off-axis viewing is not a problem because the illumination and projection lens are on axis. The response time is adequate for moving objects if progressive scan at 60 fields per second (FPS) is used. The efficiency loss from the requirement to polarize the light is a problem.

NHK and Asahi Glass are working on the use of PDLC in projectors because it does not require polarization of the light. However, PDLC has a trade-off between contrast and displayed brightness: High contrast requires a small projection lens aperture and, consequently, limited light output. Thus, according to a rough calculation of optical efficiency based on quoted screen brightness and screen gain, the NHK projector is less efficient than the TN AMLCD projectors.

Panel Addressing

Projectors that were demonstrated all used some form of progressive scan at 60 FPS. If an AMLCD is addressed with an interlaced scan, a single pixel is on for the full 1/30-sec frame time. This long display time, compounded by the marginal response time of a TN liquid crystal, gives unacceptable image smear. If the display time is shortened to 1/60 sec to reduce the smear but still scanned interlaced, the brightness and efficiency are cut in half. Consequently, progressive scan at 60 FPS is used.

In low-resolution displays that display only the vertical resolution of one field, the information from each field is simply addressed to the same lines in both fields of a frame. However, this degrades vertical resolution compared to a normal CRT interlaced display. In displays that have a full complement of vertical pixels (483 in a 525-line image), the usual addressing system is to address two lines at a time per field and shift the addressed line pair by one line for the interlaced field. This is the inverse of what is normally done on a CCD camera with interlaced scan. It gives a reasonably adequate vertical resolution with good motion rendition. Some research workers referred to an interlace-to-progressive-scan converter with more sophisticated processing. However, it was not clear that this device was being used in any of the projectors we saw.

In AMLCD drivers used for computer displays, a D/A converter was used on each column to give grey scale (usually 4-bit grey scale). For television displays, analog column switching was used for 8-bit grey scale. Some workers reported 8-bit D/A converters on each column for computer displays; however, they were not demonstrated in any of the projectors we saw. In one projector, screen nonuniformity was corrected by the drive circuit to modify black level, gain, and gamma on each pixel on the basis of stored information.

Optical Systems

The TN light valves used transmissive optics. The design of the optical systems is shown in Figure 6.1. The light from a projection lamp is divided into three color beams with two dichroic mirrors. These beams pass through three TN AMLCD panels and are recombined with two more dichroic mirrors into a single beam, which passes through the projection lens onto the screen. Because of the need for two dichroic mirrors to recombine the three beams, the back focus of the projection lens must be quite long. This increases its cost and requires more lens elements if a wide-field projection is desired.

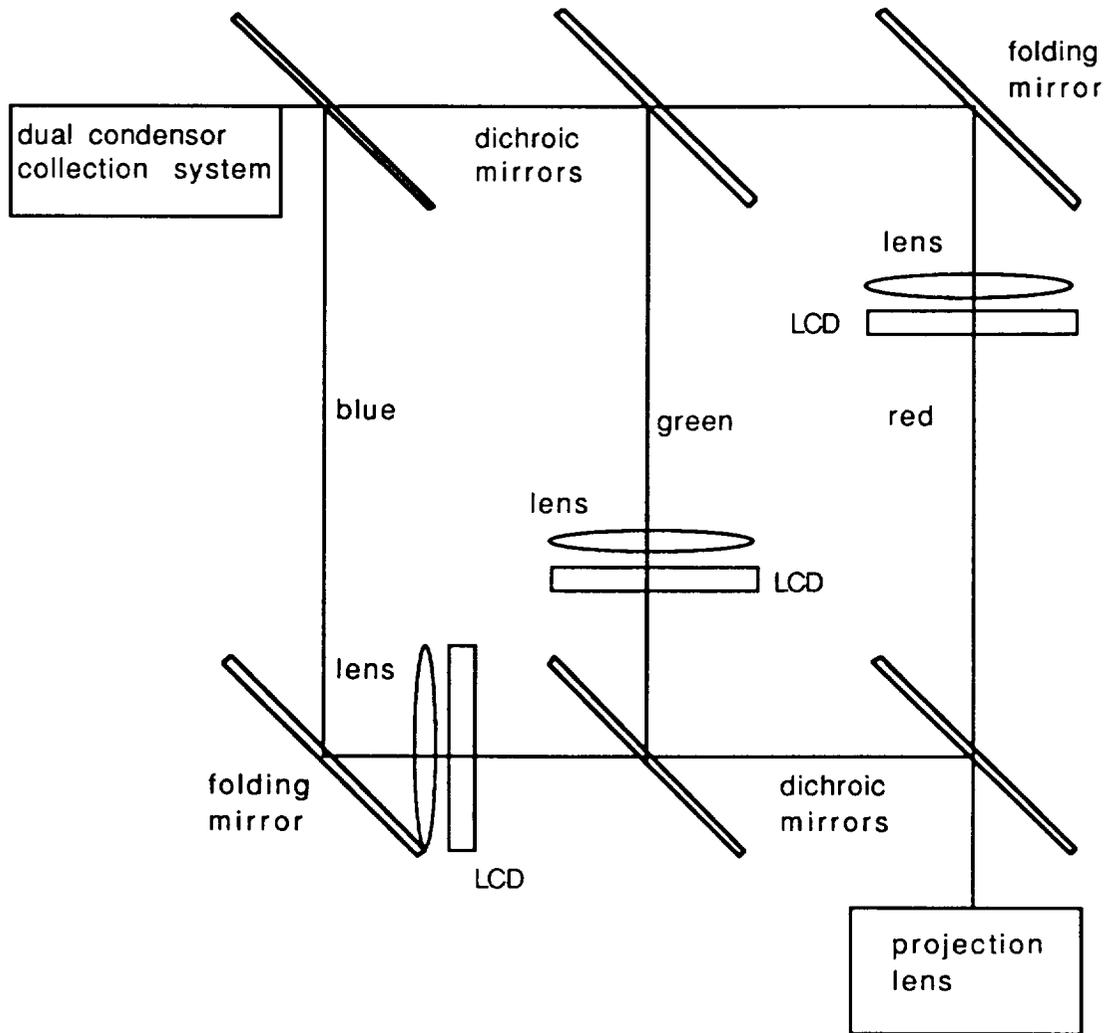


Figure 6.1. Optical Path

The projection lamp used is a metal halide high-intensity arc with a life of about 2000 hours. It has line spectra at the three primary colors but has an undesired yellow mercury line. This tends to desaturate the red and green primaries. Removal of this line optically reduces optical efficiency. The color rendition of the images we saw even with the yellow line was quite acceptable for normal program material. The arc uses a cold mirror reflector to remove infrared.

At the time of the JTEC team's visit, HDTEC was developing a back-projection HDTV display with a black matrix lenticular screen. A Fresnel field lens was used behind the lenticular screen to give better uniformity. The cabinet had a depth in centimeters equal to its screen diagonal in inches. Such a display is thinner and much lighter than a CRT display could be of the same size. The screen was developed by DaiNippon Screen. It used 2 1/2 lenses per projected pixel to minimize moire patterns. Hitachi is also developing a slim rear projector (Fukuda, 1991). These screens are somewhat similar to those developed for the GE Talaria projector in about 1961 (Glenn, 1969, 1970).

Light Output Limitations

Several projector designers were questioned about the brightness limitations of the projector design. None of the projectors produced more than about 200 lumens, which is a rather low light output for large front-projection screens for either consumer or commercial use. The GE MLV Talaria light-valve HDTV projector, for example, has an output of about 3500 lumens. Asked about the maximum light output limit, the designers generally responded that 250 watts was the highest power high-intensity, long-life, metal halide lamp made and that this fact limited the light output. Asked what limited the optical efficiency, they generally named the need to polarize the light and the inefficient aperture of the pixel display area. For 525-line displays, the panel has about 50% of its area transparent, and HDTV panels have about 30% transparency. The remainder is covered with transistors, drive lines, and a black matrix mask.

When asked what would limit the light output if a higher power lamp were available, the designers had no clear answer. However, from discussions about panel temperature, it seems that heating would limit the light output if significantly more light input was used. The greatest source of panel heating seemed to be the visible light energy absorbed by the black matrix surrounding the pixel clear area.

COMPARISON SUMMARY

Table 6.3 compares the published data about light-valve projectors made in Japan, Europe, and the United States.

Table 6.3
Light-Valve Projectors

Display	Manufacturer	Light Output (Lumens)	Resolution (TV lines) Vert./Horiz.	Screen Size (ft.)	Screen Brightness (fL)	Efficiency (Lumens/W)
Eidophor 525-line	Gretag A.G.	7000	375/800	20x26	21	0.44
Eidophor 1125-line	Gretag A.G.	4200	800/1000	10x17	54	0.26
Talaria 1125-line Arenavision	General Electric	1350	325/750	9x12	25	0.77
2LV Talaria 1125-line Arenavision	General Electric	3500	800/850	9x12	60	1.5
AMLCD	Mitsubishi NEC Philips Hitachi Sanyo Seiko-Epson Sharp	~200	~325/800	~3x5.3	~25	~1
Optically Addressed Light Valve	Hughes NHK	>1000 100?	>1000 200			? 0.3?

FUTURE RESEARCH

Efforts at this time seem to be concentrated on reducing the cost and increasing the yield of projectors of the current design in an effort to have consumer-quantity projectors available, particularly for HDTV, around the year 1995. The techniques being studied include the following:

- o The use of polysilicon on-wafer drivers
- o Adding redundancy to improve yield
- o Polysilicon on high-temperature glass rather than quartz
- o Hybrid laser-recrystallized polysilicon drivers with a-Si pixel TFTs on high-temperature glass

While there was a small effort in PDLC projectors and optical addressing, the major thrust of the effort seemed to be to concentrate on products using current system designs.

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APPENDICES

APPENDIX A PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

Lawrence E. Tannas, Jr. (Panel Co-chair)

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Lawrence Tannas, Jr., president of Tannas Electronics, is an internationally-recognized consultant and lecturer on electronic information displays--consulting on technology, market studies, designs and design reviews, technology tours of Asia, and so on. He received his BSEE (1959) and MSEE (1960) degrees from UCLA. Before beginning his consulting business in 1983, he worked as individual contributor and engineering manager at GE Research Laboratories, Honeywell, Martin Marietta, Rockwell International, and Aerojet ElectroSystems. While at Honeywell, he invented the backup reentry guidance display for the Apollo Reentry Vehicle; while at Rockwell International, he developed the engineering prototype LC display for the world's first full-scale LC display production; and while at Aerojet ElectroSystems, he perfected a manufacturing process for EL displays. In addition to display device design and development, his career has encompassed displays specifications and standards, applications, and marketing.

Mr. Tannas has been awarded seven patents, a NASA Disclosure and NASA Certificate of Recognition. He has published numerous articles as well as a book entitled *Flat-Panel Displays and CRT's*.

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William E. Glenn, Distinguished University Research Professor, is currently the director of the Imaging Systems Laboratory at Florida Atlantic University. The Imaging Systems Laboratory specializes in advanced television technology. Before assuming his present position, he was Director of the New York Institute of Technology Science and Technology Research Center (1975-1989) and Vice President and Director of Research at CBS Laboratories (1967-75). From 1952 to

1957, he was a member of the staff of the General Electric Research Laboratory, where he developed the GE light-valve ("Talaria") projector. Dr. Glenn received his Bachelor of Electrical Engineering degree from the Georgia Institute of Technology in 1946, and his MS and PhD (1952) in the same field from the University of California at Berkeley. He is a Fellow of the Society of Motion Pictures and Television Engineers, which recently awarded him the David Sarnoff Gold Medal. Dr. Glenn holds 105 U.S. issued patents and has published over 60 papers.

Thomas Credelle

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Thomas Credelle is currently manager of Portable Display Engineering at Apple Computer. He received his BS degree from Drexel University and his MS degree from the University of Massachusetts, both in electrical engineering. He joined the RCA Laboratories in 1970 and carried out investigations in electro-optic devices and holography. In 1972 he joined a group to research flat-panel displays for wall TV; he was appointed head of the group in 1980. In 1983 Mr. Credelle started a research program to develop active matrix LCDs for TV applications; he was responsible for both amorphous and poly-Si thin-film transistor research. He joined the GE Central Research and Development Center in 1986 to lead the efforts to commercialize active matrix LCDs for avionic applications. In 1991, he joined Apple Computer, where he is responsible for all flat-panel activities.

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J. William Doane, Director of the Liquid Crystal Institute and Professor of Physics at Kent State University, earned his PhD degree from the University of Missouri. He joined the faculty of Kent State University in 1965. He directs the NSF Science and Technology Center for Advanced Liquid Crystalline Optical Materials (ALCOM), a consortium of Kent, Case Western Reserve and Akron Universities. A Fellow of the American Physical Society, he has written 137 articles and holds eight patents. He is a principal investigator and executive committee member of DARPA National Center for Integrated Photonic Technology (NCIPT). He has served on the editorial board of *Liquid Crystals*, the board of directors of Optical Imaging Systems, and currently is treasurer of the International Liquid Crystal Society. He has held visiting

appointments at the University of Ljubljana, Yugoslavia; the Australian National University, Canberra; and the University of New South Wales, Sydney. He maintains applied and basic research laboratories on optics and nuclear magnetic resonance of liquid crystalline materials.

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Arthur Firester received his BA cum laude in physics from Brandeis University (1962) and his MA (1964) and PhD (1967) in physics from Princeton University. His research includes optical spectroscopy, holography, lasers and nonlinear optics, optical recording, display device production, engineering and instrumentation, amorphous silicon solar cells (research, fabrication, and application), microwave materials, devices, applications, and systems, flat display technologies, applied mathematics and physics focused on physical system simulation and electron optics design, and software and database engineering. He received four RCA Laboratories Outstanding Achievement Awards, is the author of numerous scientific papers, holds more than 20 U.S. patents, and is a member of Sigma Xi, the American Physical Society, the Optical Society of America, the Society for Information Displays, and the Institute of Electrical and Electronics Engineers.

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Malcolm Thompson obtained his BSc and PhD in applied physics in the United Kingdom, where he first worked for the Ministry of Technology on thin-film materials for infrared devices. He then became a research fellow in the Department of Electronic and Electrical Engineering at the University of Sheffield, where he studied amorphous semiconductor materials and crystalline III-V compounds. His research focused on thin-film deposition techniques, characterization of electronic properties of thin films, and device processing. He subsequently became lecturer and senior lecturer in the department. After spending a sabbatical year at the Xerox Palo Alto Research Center (PARC), he joined the center as a member of the research staff in 1982. There, he continued his work on thin-film technology and devices for product applications in scanning, printing, and displays. Currently, he is manager of the Electronic and Imaging Laboratory at PARC, which has about 80 people working on materials and devices for flat-panel displays and other large-area electronics

applications. He has built a large center of expertise at PARC, producing amorphous silicon and poly-silicon transistors on large-area substrates, which are the electronic technologies used in high-density liquid crystal displays. He was responsible for establishing a large-area amorphous silicon manufacturing facility in Japan.

He has published over 100 scientific papers, has contributed to several books, and holds several patents in the area of thin-film devices and their applications. He has received several awards for technology innovation and management, and in 1989 he was given the Xerox President's Award for his work in this area. He is presently co-chairman of several international conferences and serves on several technical society committees.

APPENDIX B. TRIP SITE REPORTS

Site: **ANELVA**
Tokyo

Date Visited: October 11, 1991

Report Author: M. Thompson

ATTENDEES**JTEC:**

Covert
Doane
Hoffman
Larimer
Tannas
Thompson

HOST:

Keiichi Katano	Senior Manager, Overseas Marketing
Hideo Mito	General Manager, Planning Office
Hideo Takagi	Senior Manager, 3rd Thin Film Engineering Division

The name Anelva is derived from Analysis, Electronics, Vacuum.

Anelva was formed in 1967 as a joint venture between NEC (51%) and Varian (49%); it was then called NEVA. In 1985, it became wholly owned by NEC, with a substantial business (¥32 billion) in semiconductor equipment and vacuum instruments. It has had substantial revenue growth, with sales of ¥53 billion in 1991.

It is organized into six business units:

- 1) Semiconductor Equipment
- 2) Thin-Film Electronic Component Equipment
- 3) R&D Equipment
- 4) Analytical Instruments
- 5) Vacuum Components
- 6) New Technology Equipment

The main focus of the discussion was on their PECVD machines used in TFT production. Anelva has 80% of worldwide market for PECVD machines and 30-40% of the Japanese sputtering market. It is developing plasma etching.

Anelva's biggest system has eight chambers, costs ~ \$5M, and has a 9-month lead time for delivery. Film uniformity is +/- 10% for a-Si & Si₃N₄ on their ILV-9330E machine. The tact time of their system is 10 mins. Contamination issues have a strong influence on tact time because of degassing issues. The systems have easy access for cleaning.

Particulate contamination in PECVD causes a major yield issue. It is difficult to measure, but they are successful in measuring particulate in the vacuum ports of the load and unload chamber using light-scattering laser detectors.

Downtime of machines in manufacturing is a major issue. They allow the chambers to cool and sand blast the coated parts. They have tried plasma cleaning at the chamber operating temperature, but it was not successful. The film quality was poor immediately after plasma etching and only recovered to device quality after 10 hrs. of deposition. Downtime of the machine depends on users but is often 30 hrs. The frequency of cleaning varies with the users from 3 days to 2 weeks. The substrate holders and frames are regularly cleaned. The shower plate contributes most to flaking and particle generation.

Particle levels are not guaranteed in their machine, but after cleaning they have measured 50-100 particles of <0.3 μm on a 4-inch wafer.

In the preheat chambers, lamp heating is used; in the cooling chamber, water cooling is used, with convection cooling with H gas. The substrates are removed from the system at 150°C and they cool in the return path tunnel to 70-80°C.

They use a simple hinged window frame substrate holder. They are not entirely happy with the automated substrate loading system.

As to the choice of machine size and number of machines, they recommend 2-3 machines per line (rather than 1 big machine) to obtain optimum productivity.

For etching, they will use a single substrate system with 2 or 3 reaction chambers. ITO is DC sputtered in Ar/O₂ atmosphere.

They believe the life of their machine is 7 years.

Their main competitors are Shimazu in PECVD and Ulvac and Leybold in sputtering. They confirmed that one company is using dry etch only (no wet etch apart from ITO).

Site: **ASAHI GLASS CO., LTD.**
Yokohama

Date Visited: October 7, 1991

Report Author: T. Credelle

ATTENDEES

JTEC:

Covert
Credelle
Hoffman
Tannas

HOST:

Yutaka Nakagawa Senior Researcher, R&D Center Co., LTD.
Tomoki Gunjima Leader and Principal Researcher, Research Ctr.
Masanori Yuki Project Team Manager, Senior Researcher, Research Ctr.

Asahi Glass is a leading supplier of glass products to the LCD industry; they also are producing LCDs in their Optrex facility (60% Asahi, 40% Mitsubishi) and are working with Mitsubishi to commercialize their TFT work (Advanced Displays, Inc.--80% Mitsubishi, 20% Asahi).

The facility we visited is the Central R&D Center for Asahi Glass. The LCD team is actually from the Electronic Products R&D Center, and the TFT team is from the Central R&D Center. We discussed three areas: STN LCDs, Poly-Si TFTs, and polymer-dispersed LCDs. TFT efforts will support new business opportunities in active matrix LCDs.

STN LCDS (NAKAGAWA)

Principal topics are fast response, wide temperature range, and color. They are also looking into basic physics of LC alignment.

Fast response: Asahi is looking at thinner cell gaps (6-7 μm now, 4-5 μm in the future) and high Δn , low-viscosity LC materials. They do not synthesize materials but do mix different compounds from the suppliers. A figure of merit described is

viscosity/ $(\Delta n)^2$; conventional materials are 1000; the new materials are 100 (smaller is better).

One remaining problem with the fast response materials is called "frame response" by Asahi; because of the fast response, the LC does not respond just to rms applied voltage, but to peak voltage as well. This leads to flicker because of the relaxation during the frame time. One fix is to use higher frame frequencies; for example, at 400 Hz the contrast ratio of one sample was 50:1, and at 60 Hz only 2:1. Higher frequencies can cause cross-talk problems, so it is not necessarily a good solution. Asahi has therefore invented a new drive scheme (not disclosed) that gets around this problem. With it they achieved a 20:1 contrast ratio at 50 ms response on a 5.7-inch diagonal, 320 x 240 8-color LCD. They are not ready to commercialize the drive scheme yet because a new controller and new driver ICs are required. The method is claimed to have lower cross-talk and lower display power; they are aiming the development at the PC market.

Color STN: Asahi is working on color STN with Optrex. They now use Shintosh and Toppan for color filters (Shintosh uses a electrodeposition method). They believe that the cost may be lowered in the future with this technique.

Viewing Angle: Asahi is developing new retardation films with controllable indices or refraction (n_x , n_y , and n_z). They have obtained higher contrast ratio and wider viewing angles without color shifts with these new films.

STN vs. TFT: The feeling of Asahi is that for color, TFT LCDs will dominate, but color STN will be suitable in the VGA and below resolution. Mono STN will dominate over mono TFT LCD because of the cost. Their prediction for 1995 is a 50/50 split between color STN and color TFT LCD for the PC market; color TFT LCD only for the workstation market; decreasing share for mono TFT LCD.

TFT RESEARCH (YUKI)

The TFT discussion centered on poly-Si R&D since the a-Si R&D is done primarily at Mitsubishi and Advanced Displays, Inc. The thrust is to develop low-temperature poly-Si processes using laser-assisted processes. Claimed advantages for poly-Si include higher mobility for integrated drivers, lower photoconductivity for projection applications (high luminance), and increased stability for higher reliability. The higher mobility also allows increased numbers of lines and therefore higher resolution.

Asahi's approach to recrystallization is to use a cw-Ar laser to recrystallize in the solid phase. The process is to deposit SiO_x, a-Si, and SiON by PECVD, to dehydrogenate at 400-450°C, and then to recrystallize with a 500-nm wavelength cw-

Ar laser drawing at 10 m/sec. Overlapping the beam paths can increase the stripe width without degradation. Each stripe is 30 μm wide. Average grain size is 30 nm, with a diffuse grain boundary. Lower leakage currents compared to other techniques was claimed; mobility is 40.

To form the contacts, an ion doping process is used; 5 Kev ions from a bucket-type source with PH_3 source gas are used. Beam current is 4.4 $\mu\text{A}/\text{cm}^2$, and the substrate is at room temperature. After a 300°C anneal, a sheet resistance of 1×10^4 ohms/square is achieved.

Comparison of a-Si and poly-Si: Asahi scientists believe that a-Si is suitable for VGA resolution, but that poly-Si will be needed for 1000-line resolution (reduces parasitic capacitance, increases aperture ratio). Asahi's goal is to develop a compatible process (to the a-Si process) in 3 years and to make projection LCDs from poly-Si by 1994-95.

New glasses: Asahi is working on a new float glass that is compatible with Corning 7059. They are not actively working on high-temperature (>600°C) glasses.

Factory: Asahi and Mitsubishi are investing in a pilot factory for TFT LCDs, a-Si at first. The stated investment was ¥10 billion for the building and ¥10 billion for the equipment. The factory is scheduled to open in July 1992.

POLYMER DISPERSED LCDS (GUNJIMA)

Asahi is one of several companies in Japan working on PDLCS. They are investigating a photopolymerization-induced phase separation process to make the PDLCS. Advantages of PDLCS include high transmission (>80%), large-area fabrication (>3m²), and high speed response (<1 ms). Applications include windows, direct-view LCDs, projection LCDs, and shutters. Limitations today include low multiplexing ratio (3:1 max.), weak backscattering, and high-voltage operation. At a recent SAE conference (1991) they described a direct-view LCD using a backlight with louvers to control the angle of the light. They achieved a 15:1 contrast ratio.

PDLCS projectors: A principal application is for projectors, and Asahi has published several papers on the subject. Present and future state of the art are:

	<u>Now</u>	<u>Future</u>
Voltage	6 - 7 V	5 V
Contrast	100 (5 deg.)	150 (5 deg.)
Hysteresis	Poor	Good
Resistivity	1×10^{11}	10^{12}

One of the most important problems to solve is the hysteresis, which is presently 0.5V (difference in voltage at 50% brightness). Recently they have achieved 0.03 V in the lab. Another problem is the resistivity, since TFTs are required to address the PDLC. New materials are needed to solve this problem. A third problem is addressing voltage; to reduce the voltage, better process control is required to improve the droplet size control.

Other companies working on PDLCs, according to Asahi, are Dainippon Ink, Seiko-Epson, Hitachi, Sharp, and Toshiba.

Site: **DAINIPPON INK & CHEMICALS, INC.**

Date Visited: October 8, 1991

Report Author: W. Doane

ATTENDEES

JTEC:

Credelle
Doane
Slusarczuk
Tannas

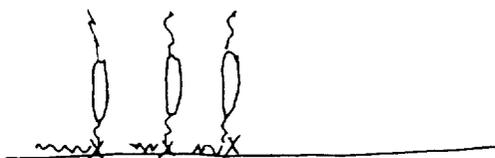
HOST:

Dr. Haruyoshi Takatsu	Technical Manager, Liquid Crystal Group
Toru Fujisawa	Liquid Crystal Research
Masao Aizawa	Group Manager, Imaging & Reprographic Products Division
Hiroshi Ogawa	Manager, Central Research Laboratories
Sadao Takehara	Senior Researcher, Liquid Crystal Research
Maeda Ryugo	Manager, Planning & Administration

Presentation by Dr. Takatsu (See attached outline "Liquid Crystal Display with High Information Content")

- o LC research started in 1963.
- o They now have a joint venture with Hoffman LaRoche called RODIC. This company is the supplier of LC materials.
- o STN materials--Important feature is voltage: hold ratio versus UV exposure and temperature.
- o Typical response time is 200 msec.
- o Important to have high pre-tilt angle and stable angle $\sim 5-10^\circ$.

Have studied molecular anchoring for different compounds on same surface.
Comment that higher tilt angle usually means weaker W_0 .
Can get normal anchoring for some materials, i.e.,



One comment and overhead by Takatsu indicated that they mix high pre-tilt material (\perp alignment) with others of low tilt to increase the pre-tilt angle. Alignment layer materials are obtained from JSR and Nissan Chem. They have a cooperative research arrangement with Nissan Chem involving alignment layers; they purchase alignment layers from Nissan Chem and JSR.

- o Image sticking--for three possible causes of image sticking. They found a material that avoids image sticking but don't understand it.
- o Uniformity of display. Controlled by cell thickness and stability of the pre-tilt angle. They believe that the "rainbow" effect observed upon filling is due to alignment layer (but may be due to material separation).

AM TN LCDs

$\rho\epsilon$ not high enough. Need pure materials, high $\rho \sim 10^{13}$ - $10^{14} \Omega\text{cm}$. Use fluorinated compounds to reduce ion solubility. These materials give $\Delta\epsilon \sim 8$. One problem is they see field induced disclinations around electrodes. They have a ternary mixture that gives $V_{90} = 1.5 \text{ V}$ at 90°C . It is difficult to control slope of a transmission curve.

MIM LCDs

Second minima are used to give high contrast. Fluorinated tolans are used to give high Δn . $\text{C}\equiv\text{C}$ (useful for PDLCs as well). Requirements for MIM and PDLC are about the same.

FLCs

There are problems with temperature range, filling and response addressing time. Spacers on substrate ($1.5 \pm 0.05 \mu\text{m}$) are formed from resist.

Tilt angle of S_c can decrease with time to reduce contrast.

They work with a nonprofit group (National Research Lab, Sagamichuhu Central Research Lab) for synthesis and research of chiral additives (dopants).

Their material has two branched chiral groups and they use dopants to reduce pitch.

For TV the response time is $\sim 20 \mu\text{sec}$ (1000 lines, line-at-a-time addressing). Fabrication and surface stabilization are problems.

Dainippon Ink (DIC) makes FLC material (see attachment). The material needs to be cooled slowly from S_A to maintain surface alignment.

They don't see any application for anti ferroelectric compounds.

ECB-LCDs

Cell thickness problems--there are not many choices of materials, reducing effort on ECB.

Their comment on Stanley's prototype: visibility poor and slow response time; small after-image that lasts ~2 seconds; transmission efficiency too poor for laptop computers.

VIDEO AND LUNCH

Sales of LC are ~3 billion yen.

Total sales are ~500 billion yen.

Main product: polymers, polystyrene, plastics.

DIC does not make color filters, but is researching dyes and pigments in a joint project with the display industry.

Competition: PDLC--Asahi, NEG
LCs--Chisso Petrochemicals

200 people are at Sukera, expanding to 400-600. Centralizing meetings are held twice a year.

PDLC

DIC interacts with many companies in this area; this is a strong component of the company. They cooperate with 24 companies on PDLC materials.

They have a prototype CdSe AM PDLC display (we did not see it working). They are working with Ghent on CdSe.

Their PDLC material contains ~80% LC, 20% polymer. Their PDLC characteristics are obtained with $d = 8 \mu\text{m}$ and the use of fluorinated LCs $V_{90} \sim 4\text{V}$. Their material needs edge seal--large "14" shutter showed fill hole on corner. Polymer material is filled, then cured. They feel PDLC is good for both direct view and projection.

GENERAL QUESTIONS BY TEAM

Q: How large AM displays are possible?

A: Problems with cell spacing for displays >20"; no problem up to 15".

Q: Rank LC Technologies.

A: **STN** - now most important.

TFT - later most important.

PDLC - third because of brightness.

MIM - fourth because less contrast (when using first minimum); good contrast with second minimum - MIM also already here in competition with TFT.

FLC & ECB - much research yet to do. Canon FLC displays look very nice but believe that they still have a problem. Canon capacity 500/month in Spring 92 at a price of 1,000,000 yen/sample.

Ch/N phase change may compete with PDLC.

Q: What about FLC?

A: Gray scale a problem. Frame modulation best means. SONY doesn't use SSFLC.

Q: Any work on retardation films?

A: No active effort.

Q: Advantage of Ch/N?

A: Fujitsu has phase change cholesteric for projection. DIC is looking at these materials.

Q: What is DIC market share in LC material?

A: ~30% in Japan. Hoffman LaRoche supplies S.E. Asia. RODIC primarily supplies Japan.

They are doing little or no work on polymer LCs.

When volume of LC gets >/~ 1 ton they will have EPA problems and need special permission from Japanese government. They are studying LC polymers for high-strength fibers only and studying FLC for opto-electronics and printers.

Q: What about temperature range?

A: If operating temp is 90°C then T_{NI} should be 120°.

Q: What about large Δn ?

They are now at about the limit ~0.22 with tolan derivatives. DIC dominates in high Δn materials. Have achieved 95% holding ratio for these compounds.

Liquid Crystal Displays with High Information Contents⁺

Haruyoshi TAKATSU
Dainippon Ink & Chemicals

1. STN-LCDs

Contrast

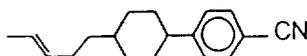
Large K33/ K11 (bend/splay)

Small $\Delta\epsilon/\epsilon\perp$

Large twist angle 220 ~ 260°

Alkenyls

e.g.



Response

Cell thickness d 4 ~ 6 μm

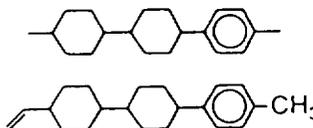
Low viscosity

Small twist angle

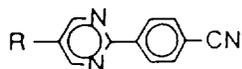
Small K33/ K11

Phenyl bicyclohexanes

e.g.



Pyrimidines



⁺ adapted from an original handout provided by Dainippon Ink & Chemicals, Inc.

Wide domain-free d/p - region

High pretilt angle 5 ~ 10°

Stable pretilt angle

HT (High Tilt) series LCs a certain group

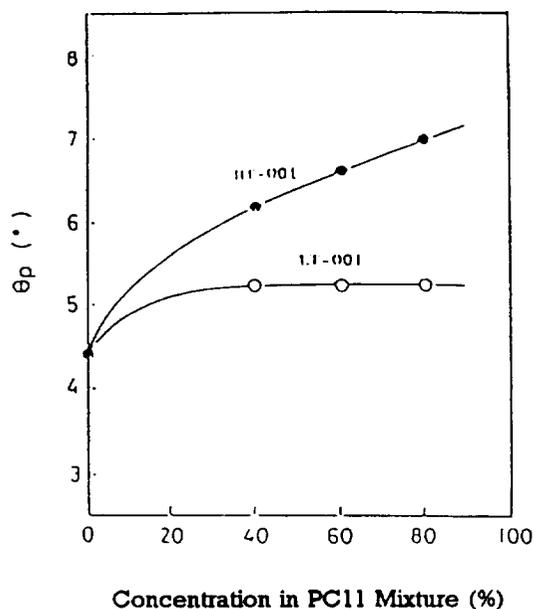


Image sticking

Polarity of alignment layer and LCs

Composition of LCs, functional groups of LCs

Uniformity of display

Homogeneity of the cell thickness

Stable pretilt angle

Chromato-like-phenomena at filling

Experimental selection of components

2. Active-matrix-addressed TN-LCDs

2.1 TFT-TN-LCDs

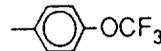
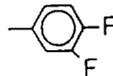
Flicker of Display

High voltage holding ratio >98%

High resistivity $10^{13} \sim 10^{14} \Omega \text{ cm}$

Stability for heat and light

Fluorinated LCs



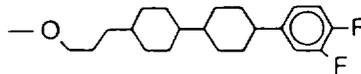
Wide viewing angle

 $\Delta n d = 0.4 \sim 0.5 \mu\text{m}$ $d = 4 \sim 6 \mu\text{m}$ low Δn 0.08 ~ 0.1

Reverse pretilt

High pretilt $2 \sim 3^\circ$

Low driving voltage



2.2 MIM-TN-LCDs

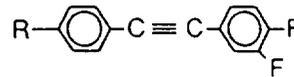
Similar requirements to TFT

Contrast

$$\Delta n d = 0.9 \sim 1.0 \mu\text{m} \quad d = 5 \sim 6 \mu\text{m}$$

$$\text{High } \Delta n \quad 0.15 \sim 0.18$$

Fluorinated Tolans



3. FLC Displays

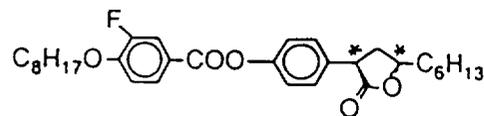
Cell spacing $\sim 2 \mu\text{m}$

Bistability at operating state

Response time

Slow for making image

Pixel $\sim 50 \mu\text{sec}$ -----> $10 \sim 20 \mu\text{sec}$



DOF-0009

Transition temperature ($^{\circ}\text{C}$)



Response Time ($\pm 10\text{V}/2\mu\text{m}$)

$65\mu\text{sec}$ (0-90%)

$28\mu\text{sec}$ (10-90%)

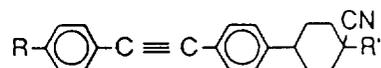
Spontaneous polarization

$24.5\text{nC}/\text{cm}^2$ (25°C)

Tilt angle

21.6°

4. ECB-LCDs

Pretilt angle $0.5 \sim 1.0^\circ$ Response thin cell $\sim 5\mu\text{m}$ Contrast Δn and cell spacinglarge Δn large $|\Delta\epsilon|$ negative $\Delta\epsilon$ large K33/K11

5. PDLC (Active-matrix-addressed)

NCAP PDLC PN-LCD Ch/P gel

Contrast

Driving voltage

Voltage holding ratio

Temperature dependence of electro-optical properties

Recent performance of PN-LCDs

Driving voltage	$4 \sim 8\text{V}$
T_0	$2 \sim 5\%$
T_{100}	$80 \sim 83\%$
$t_{0.9} (V=V_{90})$	$2 \sim 10\text{msec}$
$t_{0.1} (V=V_{90})$	$10 \sim 20\text{msec}$
ΔV_{1150}	$0.2 \sim 0.3\text{V}$
Resistivity	$5 \times 10^{10} \sim 2 \times 10^{11} \Omega\text{cm}$
$\frac{dY}{dT}$	$30 \sim 40\text{mV}/^\circ\text{C}$ ($0 \sim 40^\circ\text{C}$)

REFERENCES

1. Handout sheet
2. Brochure on DIC Central Research Laboratories
3. Annual Report, 1990, Dainippon Ink and Chemicals, Incorporated

Site: **DAINIPPON SCREEN MANUFACTURING CO., LTD.**
Date Visited: October 8, 1991
Report Author: A. Firester

ATTENDEES**JTEC:**

Firester
Glenn
Shelton
Thompson

HOST:

Yukio Ikeda	Director, General Manager, Electronics Equipment Sales Division
Nobuzo Kubo	Director, General Manager, Manufacturing Division II
Yuki Kuzukawa	Manager, Technical Coordinate Section, Hikone Plant-Electronics Equipment
Takashi Oji	Executive Vice President
Osamu Takeshita	General Manager, Rakusai Plant
Akira Yamano	General Manager, Development Department II, Rakusai Plant
Kozo Yoshida	Manager, Engineering Section I, Hikone Plant-Electronics Equipment
Yukio Yoshinaga	Manager, Planning and Promoting Department, Electronics Equipment Sales Division

MRS Asia, Inc.:
Masaharu Miki Branch Manager

Our hosts were extremely hospitable and open in our technical discussions. Our agenda was as follows:

- (i) Introductions
- (ii) DNS company video
Equipment video

- (iii) Technical discussions
- (iv) Plant tour

Several DaiNippon Screen (DNS) corporate facts are summarized below:

Established: 1943
Annual sales: \$1,067M (1991)
Employees: ~3,000

Two major business sectors:

- (a) Printing prepress equipment (60%)
- (b) Electronic equipment (40%)
 - Silicon VLSI
 - LCD panels

EQUIPMENT VIDEO

In the equipment video, the following equipment technologies were highlighted:

Wafer Equipment

- Spin scrubber removes particles $> .2\mu$; D-sonic clean available as an add-on.
- Spin coater uniform to $\pm 0.25\%$
- Spin developer
- Double-sided scrubber
- Edge-exposure system
- Wet stations
- Spin processor (wafers < 8 -inch diameter)
- Noncontact film thickness measurement (optical interference)

ALL PRODUCTS ARE MANUFACTURED IN CLEAN ROOMS!

Class 100 R&D and process training facility

LCD Equipment

- Substrate cleaner
- Cleaning processor
- Disk brush cleaner
- D-Sonic cleaner (megahertz)
- Rinsing
- Air knife dryer
- Spin dryer
- IR/UV oven

Photoresist coating: Panel coater - spin
 Roll coater - high throughput
 Hot plate oven

Film thickness measurement (optical interference)

Exposure: Proximity

Developer: Spin
 Linear spray

Etching: Etch processor (spray)
 End point detector

Photoresist stripping

Digital reader measuring instrument

DNS actively promotes equipment standards for complete in-line processing systems.

TECHNICAL DISCUSSIONS

1. **Substrate cleaner**--Specification is determined jointly by DNS and manufacturer. DNS recommends roll type for high throughput and spin type for total particle reduction.

Roller Type - leaves backside particles in 5-7 mm edge band where substrate contacts conveyor system. With air knife dry and roller brushing, 100-300 particles $\geq 1 \mu\text{m}$ in central 280 mm x 280 mm area. With air knife dry and disk brushing, it is similar to spin system and leaves 30 particles $\geq 1 \mu\text{m}$ 300 mm x 380 mm. Particle elimination ratio is $> 95\%$.

New improvements in cleaning might be dry cleaning processes, but these are not necessary.

- (2) **Coater**
 Spin coating is better than roll coating. Roll coater (conveyor) is 4x faster than spinner.

Maximum spin size is 350 mm x 450 mm, but DNS has data only up to 320 x 400. DNS believes spin machines up to 700 mm x 700 mm are possible.

Spin coater specs:

320 mm x 400 mm
 Uniformity $\leq 4\%$
 Throughput = 1/minute
 Defects - zero pinholes
 - zero particles
 Material used - 15-30 cc

DNS currently has no edge-cleaning process for rectangular substrates. They are working on this problem. Back rinse is not a problem.

At the time of our visit, DNS was developing a new type of high-uniformity roller coater, which was to be exhibited at Semicon Japan. For 1.2-1.5 μm thick coating, 5% uniformity is achieved with no defects. Contact is a most serious issue, especially for color filter production. DNS has great expectations that this technology will dramatically reduce the cost of color filters! This roller coater can be used for post-resist coating as well. In this case, uniformity is dramatically improved.

A DNS comment on slot coating is that it is low throughput.

(3) **Substrate handling**

Since substrates can only be handled by the edges, sag becomes a problem as substrates get bigger and thinner. Glass edge finish is very important for particle control. DNS believes that cassettes should be eliminated as much as possible since considerable particle generation occurs during cassette transport and handling. DNS estimates a maximum of 25 substrates/cassette based on the maximum weight that an operator can easily handle.

(4) **Color filters**

See (2) on new type of roll coating

Pigment dispersion color filter production is very promising. Production is just starting in Japan. Problem is coating.

Today, cost of color filters produced by dyeing is twice that of pigment type assuming equal yields. Future color filter costs will be reduced by 5x.

(5) **Throughput**

1 substrate/minute - active matrix

4-6 substrates/minute - STN (proximity printing)

(6) **Clean room footprint problem**

It is possible to run some equipment with only load/unload in clean room. (No equipment was mentioned that is designed for this operation.)

(7) **Maintenance**

24-hour operation (3 shifts) requires 1 day/month preventive maintenance.

(8) **Proximity printer**

Some TFT manufacturers are considering mix-and-match photolith.

(9) **DNS competitors**

Tatsumo
Chuoh Riken
Shibaura Seisakusho
Shimada Rika
ORC (USA)
Canon
Hitachi

(10) **Other**

DNS does not manufacture LC assembly equipment.
DNS estimates the cost to build a TFT line to be ¥10-20 billion for fabrication equipment only.

PLANT TOUR

In order to enter the manufacturing area, we had to be fully gowned (booties, coveralls, and hood). Entrance was via an air shower. However, the manufacturing area was designed to be Class 10,000, although DNS stated it achieves Class 3,000.

DNS equipment is fully built and assembled by subcontractors. It is then shipped to DNS for check-out and final adjustment.

We observed two in-line photoresist coaters in final check-out. These machines were designed for cassette-to-cassette operation with substrates about 300 mm x 400 mm in size. The machines cost roughly \$1 million each. Their configuration was as follows:

- (1) Dual cassette station
- (2) 90° substrate rotator and robotic load
- (3) Spin wash
- (4) Dry
- (5) HMDS
- (6) Spin coat, proximity plate
- (7) Soft bake, proximity heat, two-contact heat station; cool
- (8) Same as (2)
- (9) Same as (1)

We were also shown their R&D laboratory. This was designed to be Class 100, but achieves Class 10 to 50 under the hoods.

Site: **DAI NIPPON PRINTING CO., LTD.**
Tokyo

Date Visited: October 3, 1991

Report Author: J. Covert

ATTENDEES

JTEC:

Covert
Larimer
Tannas

HOST:

Kuniaki Kamei	Director General Manager, Central Research Institute
Masahiko Wada	Deputy General Manager, Central Research Institute
Hiroyuki Kusukawa	Assistant Manager, Central Research Institute
Fumio Takagi	Manager, R & D Promotion Department (Interpreter)
Takehiro Kojima	Division General Manager of Research, Central Research Institute
Kuniomi Tsuda	General Manager of Department, Central Research Institute
Heiju Uchiike	Professor, Hiroshima University

Dai Nippon Printing (DNP) was established in 1876 as Japan's first full-scale printing company and has grown to be the "largest-scale all-inclusive printing company in the world," with \$7.45 billion annual sales and 11,900 employees in 1990. Business includes printing on paper (60% of business); printing on plastic, metal, wood, glass, cloth, leather; packaging; decorative interior materials; and electronic parts. Electronic areas include color CRT shadow masks, color filters for image tubes and solid state imagers (video cameras, color FAX, LCD displays with line widths 10 - 500 μm), microlens array screens, photo-etching, CAD/LSI design systems, TR/IC/LSI/VLSI photomasks, video printing, electroforming, etching, stamping, and printed wiring boards. Headquarters are in Tokyo, with 20 division offices, 47 sales branches, and 20 production facilities around the world.

We were greeted by Mr. Kamei and Mr. Wada, who indicated that discussions would include LC, EL, and plasma displays with research only (no production) for plasma displays. Professor Uchiike participated in all discussions, including plans for the

SID meeting in two years at Hiroshima. He indicated HDTV displays would be on exhibit, and that Sharp was interested in sponsoring a new SID award.

Mr. Tsuda discussed color filters for LCDs. Uniformity of filter thickness is more critical for STN than for TFT LCDs, and it is easier to achieve uniformity for stripe pixel patterns vs. mosaic and triangle. They are beginning improved black matrix material research, but are currently using only 20-30 μm line width chromium black matrix (done with photo stepper 1- μm design rule lithography).

Four methods for manufacturing LCD color filters were discussed (dyed, dispersed, electrodeposition, and printing), with comparative capabilities and characteristics given for each. Dai Nippon produces color filters only for TFT LCDs (none for STN) using the dispersed method. A printing method is being developed for the low-end laptop market to save manufacturing costs using three fewer process steps. Uniformity of the ink transfer is the biggest problem in this development today. Toppan uses the dyed method which has a lower operating temperature than the dispersed method, but is best to design the filter's transmission spectrum. Shinto Chemitron produces color filters using the electrodeposition method.

Five color filters were shown. One looked like 6- x 8-inch VGA using color stripes. Two were 3 x 5 inches with triads, and two were 2- x 2-inch quads (about 512 x 512 pixels). DNP produces 30-50 μm color filters for camcorders using the dispersed method. They made some critical process changes for this application, but details were not provided.

Mr. Kojima addressed JTEC questions regarding plasma displays. The level of activity in plasma displays was discussed. NEC and DNP have stopped production. AC plasma work continues at Fujitsu (production), NEC (research), DNP (research), and Hiroshima University (research). DC plasma work continues at Oki (production), Matsushita (production), Okaya (production), NHK (research), DNP (research), Mitsubishi (research), Hitachi (research), Noritake (components only), and Electro Communication University (research). Interest in plasma is increasing for large color HDTV because of difficulty in achieving large color LCD HDTV.

Professor Uchiike commented on plasma displays. He was positive about achieving adequate driver pulse current load for large panels. He indicated phosphor efficiency is near 100% with UV excitation. He was positive about generating UV from He-Xe gas that does not generate light efficiently. He indicated UV energy does not get through the phosphor protective layer; however, the ions do damage phosphor without a protective layer.

The level of activity in EL displays was discussed. EL work has stopped at NTT, NEC, Fujitsu, and Hitachi. EL work is continued at Oki, Tottori University, Ehime University, Sharp (production), and Komatsu.

Site: **FUJITSU**
Date Visited: October 9, 1991
Report Author: W. Doane

ATTENDEES

JTEC:

Doane
Thompson
Uyehara

HOST:

Toshiaki Narusawa	Manager, Organic Materials Lab.
Akihiro Mochizuki	Researcher, Organic Materials Lab.
Shigeo Kasahara	Researcher, Organic Materials Lab.
Katsusada Motoyoshi	Researcher, Organic Materials Lab.

Scientists from flat-panel display (STN & AM) of Fujitsu were not present. Mr. Mochizuki explained that Fujitsu's STN program was very much behind others in Japan. The presentation was conducted by Mr. Mochizuki (a doctoral student of Kobayashi).

PRESENTATION OF CH/N PHASE-CHANGE HD PROJECTOR

- o Mr. Mochizuki demonstrated a 5 million pixel black and white overhead projector. He explained that they were working on a 7 million pixel one and have sold some 800 x 800 ones used to sell automobiles (work well).
- o They have front and rear projection types.
- o Advantages of Ch/N projection:
 - a. Has memory and only needs a passive matrix
 - b. High resolution (showed a road map of a section of U.S., excellent quality)
 - c. Bright display; does not require polarizers
 - d. Long lifetime (70% transmission), no absorption

- e. Quality does not degrade--unlike STN, which degrades in center of picture in overhead projection applications
- f. Writing speed - 5 seconds to write 2240 lines each with 2240 pixels (each line 2 msec), speed proportional to number of lines
- o TFT AM is needed for TV rates when using Ch/N phase change display.
- o Current display is good for publishing systems--editor wants full page with high resolution--also good for education.
- o This is cost effective: cheaper than STN.
- o The display can be manufactured on STN line using fewer steps.
- o They plan to market and sell a whole overhead projection system in competition with the STN projection system.
- o Memory is optimized (M, see figure Fujitsu.1 below) by adjusting K_{33} and K_{22} and reducing cell thickness d , now $d = 5 - 6 \mu\text{m}$ (same as STN) hysteresis (M) depends on p/d where $p = \text{pitch} \sim 1.0 = \mu\text{m}$.

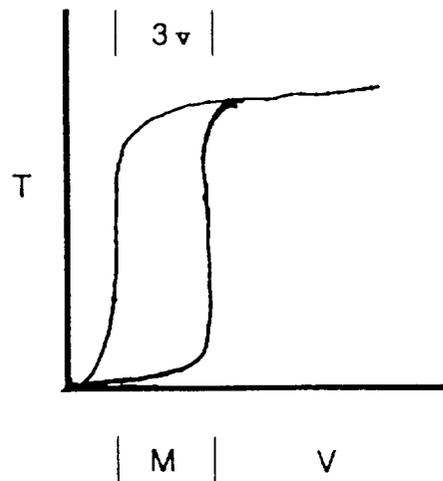


Figure Fujitsu.1.

- o Important feature on cost is the use of conventional drivers: Ch/N phase change device does this.

- o Key to their success is temperature-independent p obtained by use of following compound (see figure Fujitsu.2).

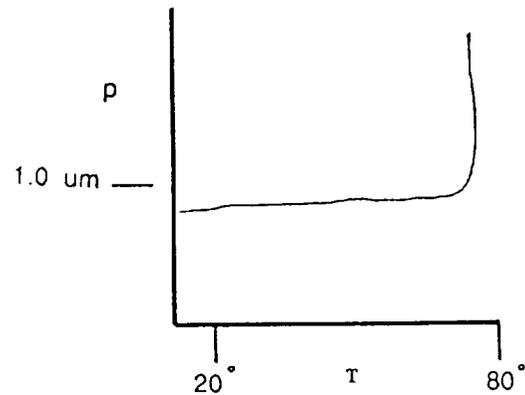
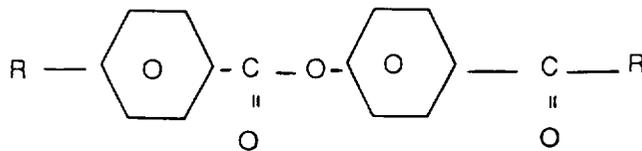


Figure Fujitsu.2

- o Characteristics of their Ch/N demo:

2240 x 2240

85 x 85 (μm)² pixel size

224 x 224 mm² size overall

Projected on to a screen ~30 ft²

Contrast ratio 4 as compared to 5 or 6 for a normal overhead viewgraph

Screen Lum 800 Cd/m²

- Trans 60%; loss is primarily due to aperture ratio of pixel

Color chart - X : Y (.419 x .380)

Drive - 12 V, 4.9-sec screen rate

- o Color is obtained by choice of pitch (p). Have made one with stacked R & G to give four colors: R, G, black (both on), white (both off). This was done in 1989.

Using R, G, yellow: 9 colors possible

Using color filter get 15

- o They demonstrated a black-and-white photo (to obtain gray levels)--it looked very nice.
- o Use homeotropic boundary layer

- o Costs--cheaper than STN--Manufacture at subsidiary
- o Direct-view displays using Ch/N phase-change techniques do not have good contrast at $\pm 20^\circ$ angles of view.

COMMENTS ON FLC

1. 30 μ sec response is needed for 1000 lines for video rates.
2. Now they obtain 120 msec for 28 V drive and 70 μ sec higher drive voltage.
3. There is a problem using TFT AM because the aperture is smaller; too small for bright projection.
4. Fujitsu can obtain stable bookshelf surface structure, which is more stable against mechanical shock (tapping display on table does not destroy it) but bending or stress on substrate destroys surface. He believes Canon uses an air support suspension system to prevent shock damage.
5. Fujitsu has a material which has wide S_A temperature range and a temperature-independent inner layer spacing to stabilize surface alignment and create the bookshelf structure.
6. The sequence is I - S_A - S_C monotropic nematic.
7. Mochizuki claims that the key to surface stabilization is a S_C material with a large range S_A and one in which the layer spacing does not vary much with temperature.
8. Their work was reported at Boulder, CO, meeting in June, 1991. The tilt angle is temperature-dependent and maximizes at approximately 20° .
9. Constant layer spacing (temp-independence) causes bookshelf structure.
10. Their S_C material is a naphthaline, which they add to a Merck mixture.

Fujitsu FLC Prototypes

196 x 120

CR is 40:1

$\pm 70^\circ$ view angle

d = cell spacing = $2.1 \pm 0.1 \mu\text{m}$

20-V drive yields 120- μ sec response

30-V drive yields 80- μ sec response

They showed us a photo (B & W) in memory state - nice.

They showed us a reflection display - nice. Cell has 80% transmission without polarizer/analyzer

GENERAL QUESTIONS BY THE TEAM

Q: What are the improvements of Ch/N projection over STN?

A: STN projection degrades in center - probably due to polarizer bleaching. STN projection can have a nonuniformity problem, particularly after use.

Q: What about VAN?

A: Nice but needs a negative $\Delta\epsilon$ which tends to be too small thus requiring higher drive voltage (limiting). Must reduce drive voltage to be able to use low cost commercial drive circuits.

Q: What about PDLc?

A: Good for projection and for large-area signs (public announcement) - need poly Si or a-Si AM for high resolution; poly-Si is better because cycle time can be reduced with improved stability.

Q: What is your opinion of the new anti-ferroelectric material reported from Europe?

A: Surface stability is better because of soft layers but the contrast ratio is not so good. Electro-optic properties are the same, about like Ch/N in switching between two states. Long pretransition region causes local nonuniformity, which affects driving; could use anti-FLC with TFT AM.

FINAL COMMENT BY MOCHIZUKI

Our host commented politely that the antidumping laws could hamper cooperativeness between U.S. and Japanese display developers.

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Site: **HDTEC**
Date Visited: October 9, 1991
Report Author: W.E. Glenn

ATTENDEES

JTEC:

Glenn
Larimer
Shelton

HOST:

Teruo Hirashima Director and General Manager

ORGANIZATION

HDTEC (High Definition Television Engineering Corp.) is a consortium of Japan Key Technology Center (which is sponsored by MITI and the Ministry of Posts and Telecommunications) and several companies--primarily NHK, Seiko-Epson and NEC.

While HDTEC has a charter that covers all aspects of HDTV, its main focus seems to be the development of a consumer HDT light-valve projector using AMLCD panels and a special back projection screen.

GENERAL COMMENTS

Mr. Hirashima was developing PDP displays at NHK before being assigned to work with HDTEC. The staff at HDTEC normally spend about half of their time at HDTEC and half at their parent company.

Mr. Hirashima feels that for large hang-on-the-wall panels, both LCD and PDP are promising. But PDP is under a handicap that only about 1/20 as many people are working on this technology as on LCD panels. Their major problem is electrical-to-optical inefficiency.

GTC is working on developing large direct-view LCD panels. Mr. Hirashima does not feel that this will be possible within this century. He feels that consumer displays

must sell for less than ¥500,000 to establish a consumer market. He thinks that within 5-10 years, back-projection AMLCD light valves can meet this objective.

LIGHT-VALVE AMLCD PANEL DESIGN

The light-modulating element in the high-definition projector is an AMLCD panel designed by HDTEC and fabricated by Seiko-Epson. A description of this device is provided in reference 3.

The driver uses poly-Si TFTs on a quartz substrate. Polysilicon has several advantages; it has high enough mobility to make it possible to fabricate the addressing drivers on the module. A self-alignment design reduces the problems of registration between successive mock exposures. The insensitivity of polysilicon TFTs to light exposure eliminates the need for a light shield over the transistor, and its high on current reduces the size of the transistor and thus improves the aperture size of the pixels.

The design uses two drivers per pixel with redundant row and column drive lines. This improves yield since drive line breaks or open transistors have a redundant back-up. In addition to redundancy, yield is improved by repairing defects. Shorts are opened with a laser. Opens are repaired by opening holes through to the poly and depositing metal from a metalorganic gas between the holes.

In the design, row lines are poly and column lines are aluminum. The column driver is a simple bidirectional switching transistor.

In order to reduce the clock speed requirements, six sectors of columns are addressed in parallel. These sectors do not match exactly in transfer characteristic. Also a defect in one of the redundant drives results in some nonuniformity. In order to produce a uniform field, each pixel has a correction for block level, gamma, and contrast. These corrections are stored in a ROM and applied to the input signal.

The panel is scanned with a progressive scan at 60 FPS. Interlaced scan signal inputs are converted to progressive scan using line interpolation and time-base correction to derive all of the active lines from the current field of information.

OPTICAL SYSTEM

The optical design of the projector is described in reference 4. The light source is a 250-watt metal halide arc with line spectra at the primary colors. It unfortunately also has a 580-cm mercury line that tends to desaturate both red and green.

Dichroic mirrors are used to separate and recombine the primary colors. Since two dichroic mirrors are required between the panel and first element of the projection lens, a rather long back-focus is required for the lens.

The panel itself has 960 x 1439 pixels with an aperture of 30% and a diagonal of 4.55 inches. The contrast ratio is 70:1. The optics in the cabinet are folded to give a 55" diagonal image with a cabinet depth of 55 cm. The optical throw distance from lens to screen was 1.5 meters. The optical efficiency was somewhat less than one lumen per watt. The exact number was not known because of severe shading in the image. The corner intensity was about 30% of the intensity in the center.

The present design uses air-cooled panels. When asked what limited the light output if higher power light sources were used, the answer was not known. However, it seemed that increased leakage from panel heating would be the limit if significantly more light flux was used to illuminate the panels. It was felt that about 70°C would be the upper limit that could be tolerated using larger pixel storage capacitors.

SCREEN DESIGN

The projector uses a special back-projection screen (described in reference 5) to provide a high-contrast image in the presence of ambient light. The screen uses a fresnel lens to provide illumination uniformity, lenticular lenses to give a wider horizontal viewing angle, and a diffusing plate. To minimize moire patterns between the pixel structure and the lenticular plate, a pitch is used with the lenticles that has 3.5 lenticles per projected pixel. The half-integer number was felt to be important to minimize moire.

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6. Kunio Yoneno, Hiroshi Kamakura, Junichi Nakamura, Akitaka Yajima, Joji Karasawa, Tadaaki Nakayama, Masanori Ogihara, Yoko Miyazawa, Shunji Banda (Seiko Epson Corp.) and Norihisa Okamoto (High Definition Television Engineering Corp.), "High Definition Front Projector Using Poly-Si TFT LCD."

Site: **GIANT TECHNOLOGY CORPORATION
AND HITACHI RESEARCH LABORATORY**

Date Visited: October 2, 1991

Report Author: A. Firester

ATTENDEES

JTEC:

Covert
Firester
Slusarczuk
Tannas

HOSTS:

Eiji Kaneko	Chief Researcher, GTC-Director, Giant Electronics Research Laboratory
Shinzo Matsumoto	Engineer, TFT Display Department
Yoshiaki Matsumoto	LCD Products Sales Engineering, Tokyo Office
Yoshiharu Nagae	Senior Researcher, Planning Office & The 9th Department
Kohzoh Odawara	Senior Chief Engineer, Electron Tube Division

Our agenda for this meeting was as follows:

- (i) Introduction (All)
- (ii) Review of Sarnoff p-Si (Firester)
- (iii) GTC (Kaneko and Nagae)
- (iv) LCD business issues (Odawara)
- (v) Technical discussions (All)

This report follows the agenda above and covers items iii-v.

(1) Giant Technology Corporation (GTC)

- GTC was organized for the period March 1989 to September 1994.
- 70% of the funding is provided by the Japan Key Technology Center. The remaining 30% funding is provided by the member companies.

- Consists of 17 companies, including Thompson CSF and Hoechst.
- The goal is to develop basic technology for a 1-meter flat display.
- Funding was reduced to ¥2.8 billion for the 5.7-year period. The goal was reduced to do only very basic research.

The GTC organization is shown below.

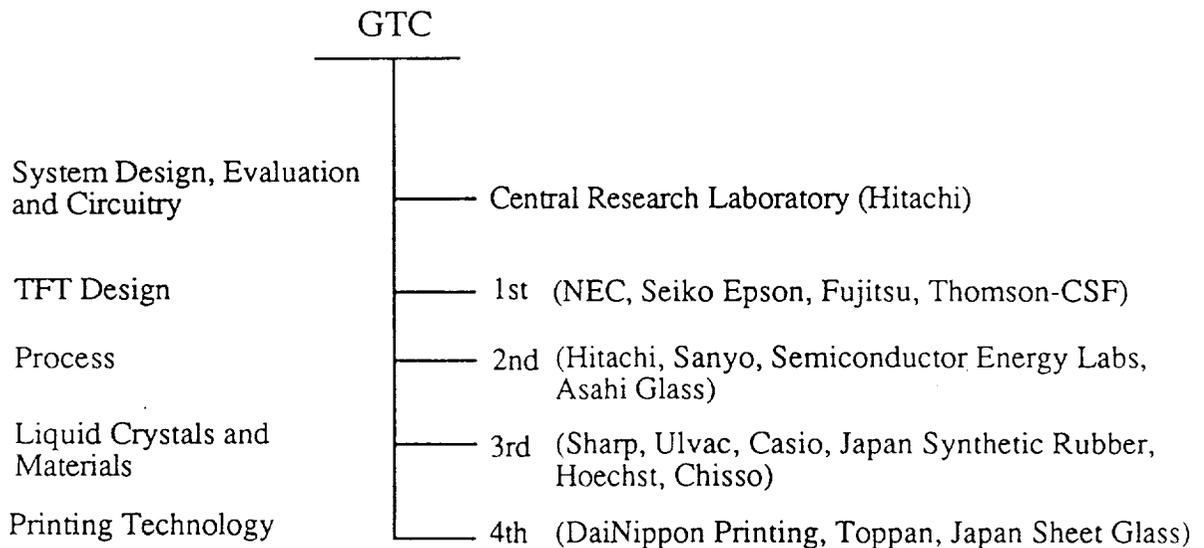


Figure GTC.1. GTC Organization

Nagae provided results to date on the TFT printing process. (These results will also be the subject of a paper at the IDRC).

- Goal is 1-minute cycle time with resolution of about 20 μm lines and spaces. Use of step and repeat exposure is not possible for 1 meter. Throughput vs. cost is too low.

- Actually achieved resolution of 3 μm features. Built polysilicon p-mos TFTs with $W/L = 19 \mu\text{m}/3 \mu\text{m}$ on 100 mm square glass substrates. Glass used is Corning 7059 or Asahi AN. Also built shift register and inverter circuits.
- Process used is same as conventional Hitachi p-mos:
 - o Self-aligned gate
 - o Ion implantation
 - o Temperature $< 600^\circ\text{C}$
 - o Mobility $\approx 40 \text{ cm}^2/\text{v}\cdot\text{sec}$
- Polysilicon is desired for peripheral integrated drive circuitry. For $> 10''$ to $14''$ diagonal displays p-Si integrated drive circuitry is mandatory.

TECHNICAL DISCUSSION

- Hitachi is still researching the problem of p-Si leakage current. Their best results have been achieved on both silicon and glass substrates. Reproducibility is inadequate for a production process.
- A much shorter process turn-around time is needed to accelerate the development of p-Si.
- Hope to use Corning 7059 for a p-Si process below 550°C .
- Basic process is not defined. Off current problem. Elimination of ion implantation is desired.
- Hitachi strategy is to develop a p-Si process that has maximum commonality with a-Si. Insertion strategy is to add special p-Si processes to existing a-Si production line and run both p-Si and a-Si in parallel at first.
- Mobara production:
 - Difficult to identify yield bottleneck
 - Substrate is 200 mm x 270 mm
 - One 10-inch diagonal display per substrate
 - Use Canon MPT 2000 stepper
 - Production of 10-inch color TFTs (for Hitachi Flora Laptop) is about 1000/month
 - Aluminum anodization equipment can handle a 20-inch panel
 - A heat bias treatment is used in the process
 - Dry etch silicon; wet etch Al and ITO
 - Dip-coat Corning 7059 in silica

PECVD is very dirty; need better equipment

ESD is a problem

Two point defects/panel average

Laser repair by cutting

Experimenting with 1:1 holographic printing

Mobara is producing few 5-inch and 6.3-inch displays. They concentrate on 10-inch because it is more profitable. Hitachi now buys LCD driver ICs. They prefer bigger displays because they use the same number of ICs per display.

Line runs 24 hours/day, two shifts, about 250 people: 100/shift, and about 50 process engineers.

Site: **HOSIDEN**
Date Visited: October 3, 1991
Report Author: L. E. Tannas, Jr.

ATTENDEES

JTEC:

Covert
Credelle
Larimer
Slusarczuk
Tannas

HOST:

Shigeo Aoki	Executive Vice President
Yasuki Iwano	Senior Staff, Technical Administration
Shoichi Matsumoto	Executive Deputy Director, R&D Center
Yasuhiro Shigeno	Manager, R&D Center
Yasuhiro Ugai	Manager, R&D Center
Yasuhiro Matsushita	Assistant Manager, R&D Department

The visit included a review of the Hosiden exhibit at the Japan Electronics Show and a dinner meeting at the New Otani Hotel, Tokyo, hosted by Mr. Aoki. During the meeting, Mr. Aoki answered most of the questions, usually after brief discussions with his staff. Some of the key points made in response to our questions were as follows:

- o Color CRTs will eventually be replaced by color LCDs in office automation.
- o For notebook computers, black-and-white LCDs are still preferable because of power consumption and cost issues.
- o For desktops, 12- to 15-inch displays are believed to be preferable to 10-inch displays used today in laptops.
- o It is believed that MIM LCD technology cannot compete successfully with TFT LCDs.

- o It is believed that FLCs have serious problems with cell gap control, shock and vibration sensitivity, addressing speed, etc. It is not known if Canon has solved the problems such that they are ready for production.

Hosiden had an excellent presentation at the Japan Electronics Show, showing their 10- and 15-inch active matrix a-Si LCDs. Unlike at previous Japan Electronics Shows, they did not show any avionics displays. However, they did show the wide viewing angle display developed for avionics using a Honeywell patent called "halftone technique."

Hosiden is continuing to support avionics direct to Honeywell.

Hosiden is a leader in a-Si LCDs with a 15-inch full-color 640 x 480 pixel, 1280 x 800 pixel, and other high-performance size displays.

New technical breakthroughs:

- o Low resistance gate and source bus wiring material for large displays
- o High-speed drive circuit using parallel processing and ASICs
- o Improved connections using TAB for high-resolution interconnects
- o Uniform TFT film using ion-doping technology to give uniform coverage over the entire substrate

Hosiden estimates the LCD market to be 200 billion yen in 1990, growing to 1,000 billion yen by 1995, which is an annual rate of about 38%.

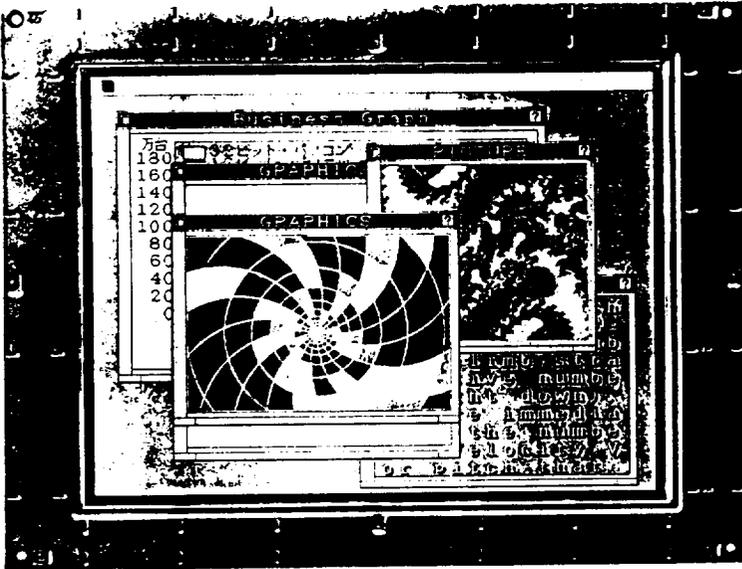
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HOSIDEN

液晶表示素子 Liquid Crystal Displays

アクティブLCDモジュール/ACTIVE MATRIX LCD MODULE



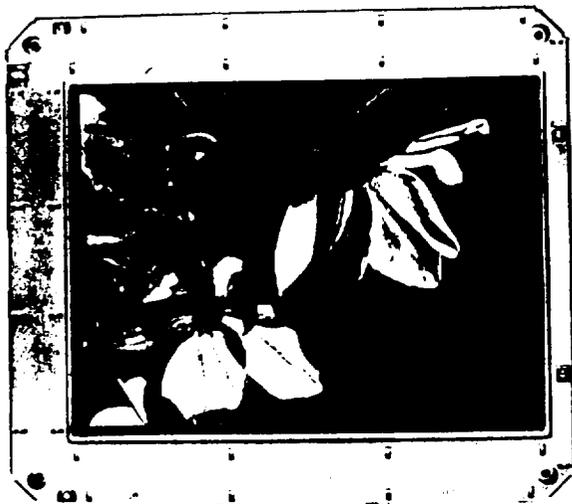
10.4" Multi-Color HLD1013

■アクティブ LCDモジュール

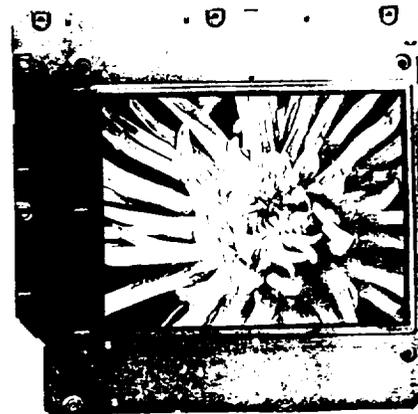
- 当社独自のTFT構造および量産技術により、高精細、高コントラストで色再現性に優れた高品位カラー画像が得られます。アクティブLCDの高速応答性、広視野角の特長とともに高輝度で均一なバックライト、高密度実装技術による軽量かつコンパクトなモジュールが実現しました。
- ラップトップパソコン、情報端末機器などの各種OA機器用ディスプレイ、ならびに TV、VTR、自動車用などのディスプレイとして広範囲な用途への適用が可能です。

■Active Matrix LCD Module

- Our original TFT structure and mass production technology have created an innovative, active matrix LCD module capable of generating high-quality color images with high resolution, high contrast and superior color reproducibility. The module is fast in response, has a wide viewing angle, and equipped with a backlight of high luminance and uniformity. It is made light and compact by employing our high-density mounting technology.
- Applications: Displays for various office automation equipment, such as laptop personal computers and information terminals, and TVs, VCRs and automobiles.



7" Full-Color HLD0709



5" (PAL) Full-Color HLD0509

Figure Hosiden.1.

サイズ Size	9.5" (Color/ Monochrome)	7"	5" (PAL)	5" (NTSC)	10" (Monochrome)	10.4"
ドット数 Dot Number	960 × 960	720 × 460	480 × 270	480 × 240	640 × 400	1920 × 480
カラードット Color Dot	640 × 480	480 × 230	320 × 135	320 × 120	—	640 × 480
ドットピッチ Dot Pitch (mm)	0.20 × 0.15	0.20 × 0.23	0.21 × 0.27	0.21 × 0.32	0.33 × 0.33	0.11 × 0.33
有効表示範囲 (mm) Effective Display Area	192 × 144	143 × 106	101 × 77	101 × 77	211 × 132	211 × 158
カラー配列 Color Arrangement	RGB Delta Arrangement					
					—	RGB Stripe

Figure Hosiden.2.

Site: **IBM JAPAN, LTD.**
Yamato

Date Visited: October 2, 1991

Report Author: T. Credelle

ATTENDEES

JTEC:

Covert
Credelle
Hoffman

HOST:

Shinichi Hirano

Mr. Hirano is a senior staff member in charge of TFT LCD development at IBM Japan. We spoke with him for two hours and had a tour of the IBM development line. He presented a historical perspective of the IBM/Toshiba relationship and how it was working to develop AMLCDs for office automation use by the two companies.

IBM/TOSHIBA PROGRAM

In late 1985, IBM decided to invest in AMLCDs for future products; they chose Toshiba for a partner and entered into a two-year joint development agreement in 1986. The first year, IBM engineers worked at Toshiba to learn the technology while building a development line for large substrates at IBM Yamato Labs (PC division R&D and hard drive R&D). The second year, Toshiba engineers came to IBM to work on the new line and to develop a 14.25-inch color AMLCD based on the jointly-developed a-Si technology. The clean room is a laminar downflow clean room (Class 100, 1,000 and 10,000); the total area is approximately 1000 m². It used the best equipment at the time, although Hirano said that some of the equipment is now a little out-of-date. Lines were established for TFT, color filters, and panel assembly. He called panel assembly an "agriculture" as opposed to "industry." He said that even if "the best seeds" were sown, there was no guarantee of a "good crop." In March of 1988 the 14-inch panel was completed (720 x 550 color quads RGBW, 0.2 mm subpixel). The partners made a total of 20 panels.

A decision was then made to continue the joint development and to also invest in a factory. In the interim, a pilot line was established at Himeji by Toshiba. The factory is a 50/50 deal, with each company getting 50% of the output. Display module design is separate, since it is dependent on the portable computer design and other applications. The first products will be 512-color AMLCDs, but they are evaluating 4-bit designs. IBM/Toshiba will demonstrate a 13.8-inch, 1152 x 900 pixel color LCD at JES and Comdex. Mr. Hirano claimed that he was told that the pilot line was achieving approximately 50% yield. The DTI factory is now operating; he did not say what the yield or production capacity would be. He did say it would be the largest such facility in Japan (60 m x 90 m x 31 m high, 4 stories).

TECHNOLOGY DISCUSSION

Gray scale--IBM is working on 6- and 8-bit versions.

Panel size--IBM thinks 16 inches is feasible and will replace 20-inch monitors.

Penetration into CRT market--estimates 50% by 2000.

Aperture ratio--will be improved from current 30-40% to >60%.

Mobility--IBM and Toshiba are working on higher mobility a-Si.

Poly-Si--IBM doesn't believe it will be successful for large sizes; interconnection to external drivers is more economical than building poly-Si.

Integrated drivers--it should be possible to do some kind of auxiliary driver circuit in a-Si.

Backlight--looking at improved designs and are working with suppliers of lamps to improve brightness. He mentioned an experiment where brightness was weighted higher in the center; it looked brighter than a comparable unit with uniform brightness and did not look nonuniform.

Costs--costs will be gradually reduced through small improvements (the "Japanese way"); and through process equipment improvements.

Ferroelectric LCDs--might be competition for AMLCD but gray scale and manufacturability are a problem ($\pm 0.05 \mu\text{m}$).

TOUR

We had a brief glimpse of the development line. The line consists of single pieces of equipment in most cases. The photo lab uses a Nikon stepper with a 100 mm field; IBM jointly developed its own spinner with an equipment manufacturer for resist coating. The PCVD has six chambers (four active). The sputtering system has three active chambers. Two laser repair systems are in use, one for cutting and one for adding material. Color filters are made by IBM. Backlights, TAB packaging, and so forth are also done at IBM Yamato. A lot of attention was paid to safety, with an excellent monitoring system. They have had no accidents.

We did not see any working panels because they were at Comdex and JES.

	<u>Dyeing CF</u>	<u>Printing</u>	<u>Pigment</u>
Pattern			
Process	Long	Short	Medium
Cost (main factor is yield)	100	80	100
Working display	Present 14" Max 20"	Present 4" Max 10"	Present Max 20"

In summary, the main emphasis is on reducing cost of filters.

Figure IBM.1.

Site: **MATSUSHITA**

Date Visited: October 7, 1991

Report Author: A. Firester

ATTENDEES

JTEC:

Firester
Glenn
Shelton
Thompson

HOST:

Yutaka Miyata	Senior Researcher, Display Technology Research Laboratory, Audio Video Research Center
Isao Ota	General Manager, Display Technology Research Laboratory, Audio Video Research Center
Mamoru Takeda	Senior Engineer, Liquid Crystal Display SUM
Yoneharu Takubo	Engineer, Liquid Crystal Display SUM
Hiroshi Yamazoe	Manager, Display Technology Research Laboratory, Audio Video Research Center

We were hosted by Mr. Ota. He first explained to us the organization of the Matsushita LC Display Strategic Unit for Development and Manufacturing (LCD SUM). This is an internal organization of both development and manufacturing functions. LCD SUM is a profit center; sales of products supports R&D. Figure Matsushita.1 outlines the structure. Matsushita prepared an excellent detailed written response to the questions we submitted in advance.

All Matsushita R&D is funded by the company. They have some connections with Osaka Industrial University for basic R&D. The flat-display strategy is first internal use only and OEM only if there is excess capacity. First-stage applications are workstations, followed by AV (projection) and direct-view TV.

Matsushita will focus only on large-size panels in their new line.

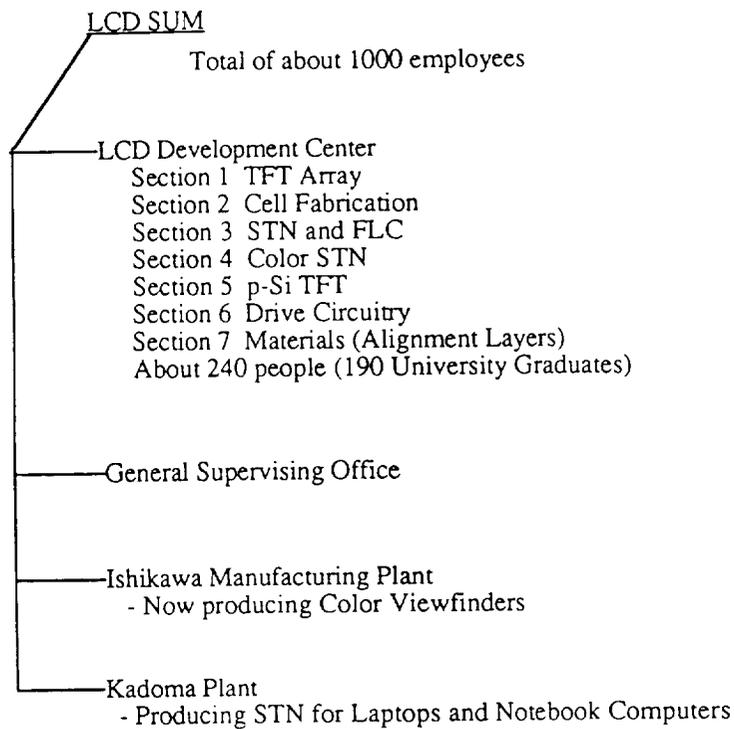


Figure Matsushita.1

WORLD RECORD COLOR AMLCD SHOWN AT JES

- o 15-inch diagonal
- o 256-level gray scale, 16777 K colors
- o 374 x 275 x 22 mm overall size; 1.7 kilograms
- o 15.02-inch diagonal; viewing area = 301 mm x 235 mm
- o 0.261 mm pixel pitch; 30% aperture ratio
- o Vertical stripe RGB color filter
- o (1152 x 3W) x 900 TFTs
- o 50 msec = $T_r + T_f$ @ 25°C
- o CR > 50 (best is 100)
- o 60 cd/m²
- o Viewing angle R/L $\pm 40^\circ$; U + 30°; D -10° @ (CR > 10)
- o Total power = 46 watts; VLSI interface ~ 20W; Backlight ~ 20W
 - o Video drive circuit - specially designed and produced by Matsushita.
 - o Analog memory + operational amplifier; 12 parallel channels to handle bandwidth; TAB interconnection 60Hz noninterlaced scan
- o Fabricated at Ishikawa; designed at Kadoma
- o Plan is to incorporate this panel into a Matsushita product (SPARC workstation) in 1992

MANUFACTURING AT ISHIKAWA**"Old" line:**

Manufacturing a-Si viewfinders
6" x 6" substrates
16 viewfinders/substrate

"New" line:

32 cm x 40 cm
Capacity 5K substrate starts/month; a lot of unused space to add another line and easily go to 10K/month.

Color filters:

Currently buying; most expensive component; 10-inch diagonal about ¥20; 15-inch more than ¥60; expectation is that eventually costs will come down.

Major issues:

Photolith--Best long-term throughput potential is Canon-type exposure; currently Canon can expose four 10-inch diagonal displays per substrate (Matsushita used a Nikon 1:1 stepper for the 15-inch prototype).

PECVD--Needs long cleaning times, which must be reduced. Matsushita is currently researching cleaning methods.

Undercoat--APCVD SiO₂ used for both a-Si manufacturing (and low-temperature polysilicon) for reliability on 7059 glass.

ESD--A shorting circuit on the periphery of first metal layer is used through the entire process.

Test and repair--Process monitoring is only sampling of layers, e.g. S.N. optical gap. Fifteen minutes/panel for visual testing of fully assembled displays (repair of lines only).

POLYSILICON

High-temperature p-Si cannot be used to fabricate HiVision drive circuitry (projection discussion, Takeda).

They are investigating both high-temperature and low-temperature processes. HT suitable only for small sizes (viewfinders) and LT for 1- to 3-inch diagonal applications (projection).

Matsushita is studying excimer laser recrystallization of PECVD silicon. Uniformity is difficult; using multishot methods. Experiments only. Requires about 200 seconds for a 6-inch diameter wafer; not optimized. Mobilities achieved are 50-100 cm²/V-sec N-type and 20-50 cm²/V-sec P-type. Achieved high mobility using sputtered silicon, but there are many pinholes; sputtering is not suitable for large sizes.

For EDTV, mobilities of 50 (N) and 20-30 (P) are all that is needed. V_T is more critical. Currently $V_T = 10$ to -15 (P) and $V_T = 0$ to $+2$ (N).

They expect to be able to use p-Si on glass for peripheral drivers by 1995.

LPCVD is difficult to use for sizes larger than 300 mm x 300 mm; therefore, interest in PECVD.

Many approaches are under study for doping: ion shower, n-type amorphous silicon, gas-phase doping; ion implantation too expensive.

Gate insulator processes are under study are LTD, APCVD SiO₂, and PECVD SiN. Problems still exist with interface states and bulk defects. Best so far is APCVD SiO₂.

PROJECTION

a-Si is suitable for projection. Optimum size is 3-inch diagonal.

Aperture ratio 30-40% @ 3-inch diagonal achieved 1 lumen/watt with an experimental transmissive system (Reflective LCD - 0.2 lumen/watt)

$$T = \tau_r + \tau_f = 70-100 \text{ msec}$$

Light output is limited by a-Si photo conductivity. For home use the goal is 250 ft-lamberts on a 40-inch diagonal screen. This results in 400,000-lux blue light on a 3-inch diagonal light value. This value is safe.

Demonstrated 200 lumens output using a 250-watt metal halide lamp. This lamp provides 80 lumens/watt.

Maximum LV temperature should be less than 70°C with air cooling. The LC would operate up to 100°C but reliability is a concern at temperature > 70°C. Using the above lamp, the LV temperature is ~60°C.

Projector lens f/# = 4.5

Progressive scan using two-line driving method. Matsushita prefers two-line drive for moving images and single line drive progressive (using a frame store) for static images.

They have an interest in single LV color sequential projection to reduce the cost of the projector.

FELCD

Matsushita has been working on FELCD for many years.

They have fabricated a 10-inch diagonal view display and a four megapixel projection display, which requires 500 msec for complete refresh.

They favor FLC for high-information-capacity static displays, and use partial addressing to handle mouse movements.

To achieve gray scale, possible techniques are frame rate modulation, subpixels. However, their ultimate goal is multidomain gray scale.

PDLC

Expect use for projection in 1995.

Backlight

Note: Matsushita manufactures and OEMs hot cathode fluorescent lamps and inverters.

Their 3 mm diameter lamps have an efficiency of < 35 lumens/watt. They would like to use cold cathode lamps for color sequential.

Site: **MERCK JAPAN, LTD.**

Date Visited: October 11, 1991

Report Author: W. Doane

ATTENDEES

JTEC:

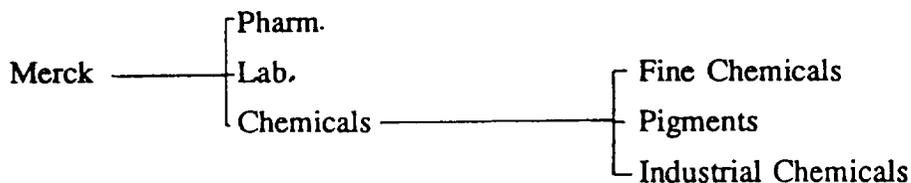
Covert
Doane
Hoffman
Larimer
Tannas
Thompson
Uyehara

HOST:

Dr. Bernard Rieger
Dr. Shouhei Naemura
Erwin G. Spendler

OVERVIEW OF COMPANY BY MR. SPENDLER

With \$2 billion in annual sales, Merck Japan has about 2000 employees.



Industrial chemicals include liquid crystals, electronic chemicals, evaporations (for eyeglass or optic coatings), solvents for etching and cleaning, UV initiators, etc. Most applications are for optics.

Main liquid crystal business includes: Japan, S. E. Asia, small business in Europe and U.S. (see Table Merck.1). Taliq, Inc. buys the largest quantity of LC in U.S.

Breakdown in sales:

U.S.	Japan	S.E. Asia	Europe
1-2%	70%	25 - 30%	1 - 2%

Merck claims more than 50% of the market. They have strong patent position; therefore their competitors end up buying from them. 13 - 15 tons of LC/year is used in the Japanese market. RODIC--joint venture between LaRoche and Dainippon Ink has another 30% of the market.

R & D of liquid crystals and supplies from Merck include:

- Merck - Darmstadt, Germany (synthesis, mixtures - do everything)
- BDH - Poole, England - 100% subsidiary (PDLCS)
- Merck Japan- Tokyo (Mixtures only)

General Questions by the Team

- Q: Please comment on the patent situation with cyanobiphenyl materials.
A: Two years left on cyanobiphenyl (CB), but they also have many mixture patents so that even though other companies can make CBs, they cannot use them.
- Q: Where are LCs synthesized and mixed?
A: Synthesis is primarily at Darmstadt (largest). The BDH facility at Poole is the principal developer of PDLCS. No synthesis of LC at Merck Japan, but they put together mixtures.
- Q: Do you have set mixtures you sell?
A: No, normally each sale involves mixtures prepared for specification. Each company wants different characteristics. Every mixture is custom-designed and has a code name to keep a company's mixture proprietary. It can take a year to get the mixture correct. It is entirely Merck's responsibility to get the mixture to the manufacturer's specs. Then, as soon as they meet those, the manufacturer tightens the specs for the next order. One Japanese customer uses 260 different mixtures. Merck does make recommendations to customers to use different alignment materials. Some companies have their own ideas, but generally are more willing to listen to Merck's recommendations. Customers often remix or change the mixtures that Merck supplies them. Purity is always an issue.
- Q: Prices?
A: \$2.85 - \$10.00 per gram depending upon material. Cost of LC is 1 - 2% of total cost of TN and STN display - even less for TFT.

Q: Do you sell material for alignment layers?

A: No, but study how these materials align on alignment layers. Merck often gives advice to companies, but more often the companies have a fixed idea on alignment layers.

Q: Do you sell material for color filters (CF)?

A: No, their pigments are used for other things. Merck does not supply pigments for Toppan's color filter business.

LIQUID CRYSTAL MATERIAL R&D--DR. RIEGER

Dr. Rieger was asked to prepare a table of material specifications normally used for the various display technologies (see Table Merck.2).

General Questions by the Team

Q: Material interests for STN?

A: Believes that STN's greatest physical limitation is the slow switching time (viscosity of materials). Want low viscosity and large K_{33}/K_{11} to shorten the switching time. Goal is to improve switching time to compete with AM TFT/TN.

Trade-offs between Δn and d when d is reduced to improve response time.

Q: Materials for MIMs?

A: The development of MIM seems to be going toward using the 1st minimum and then using phase-compensation films.

Q: What values of Δn are achievable?

A: Like higher tilt angle, but tilt angle becomes unstable at higher angles.

Q: Are temperature ranges a subject of interest?

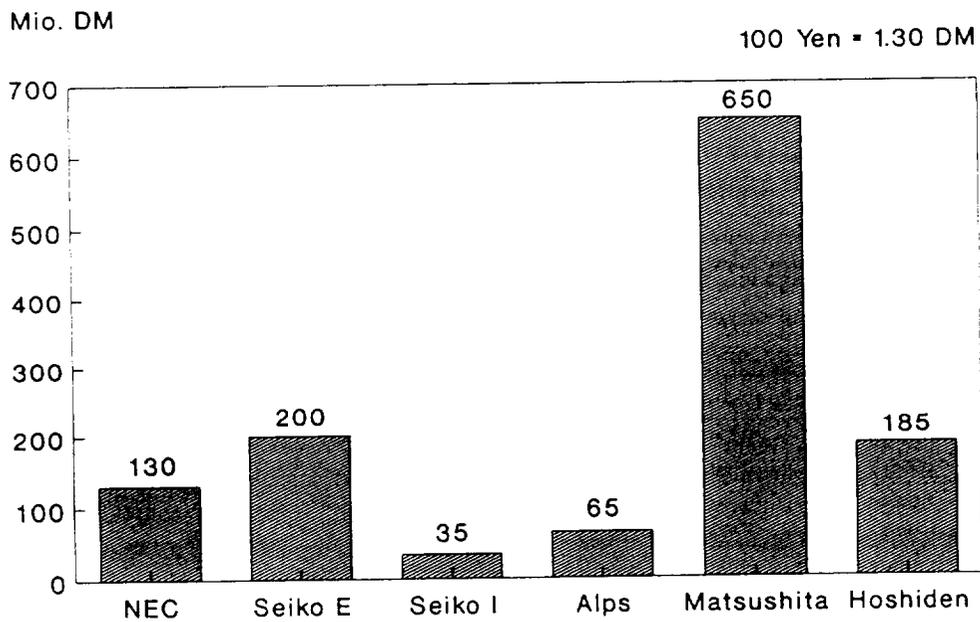
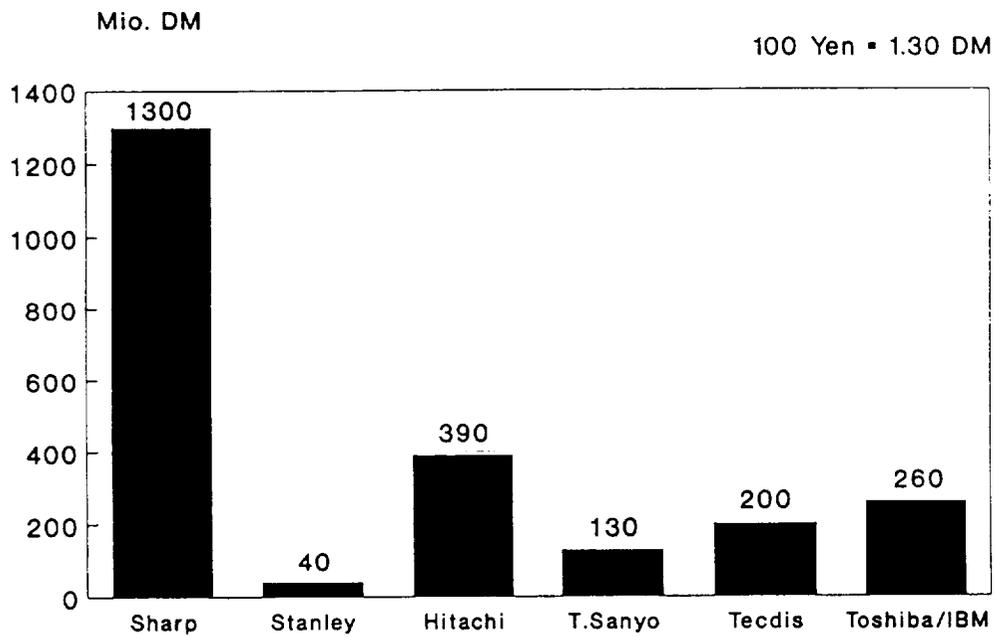
A: Often need to sacrifice temperature range to achieve lower drive voltage. Max range is $\sim -40-100^\circ\text{C}$, very difficult to improve on this. There are often many trade-offs in LC materials selections. Storage temperatures do affect the properties of the materials. There often are problems with the LC reacting with other materials in the display, e.g., the glass or sealant.

Q: Materials for TFT?

A: Usually want lower elastic constants to reduce drive voltage since there is a limit on $\Delta\epsilon$.

- Q: What resistivities are attainable?
A: $\sim 10^{13}$ Ωcm are possible. Use fluorine materials for high ρ . Usually low V_{Th} have low ρ .
- Q: Where do you see improvements in materials?
A: Don't see anything radically different in the future - just fine tuning.
- Q: How do you compete?
A: Technical performance, prices.
- Q: How do you check for chemical deterioration?
A: Monitor resistivity - good measure of stability.
- Q: Is everyone using polyimides for alignment layers?
A: Yes - almost.
- Q: What about damage from extreme low and high temperature?
A: Their measurements stop at -40°C . If material doesn't crystallize after 1000 hrs., they claim it is stable.
- Q: Do you have LC materials below 55°C ?
A: Yes, two materials.
- Q: Who are the suppliers of alignment layers?
A: Nissan Chem - JSR, Hitachi Chemicals (small).
- Q: What are other alignment layer compounds?
A: Only polyimides now commercially available.
- Q: How much can you control pre-tilt with compound concentration?
A: Pre-tilt $1-3^{\circ}$ can vary, but usually customer does not request this.
- Q: Does Merck participate in GTC or HDTEC?
A: Merck does not participate in GTC or HDTEC either directly or indirectly - their customers don't tell them too much about their interests. Merck has no immediate plans to make a large-scale synthesis effort in Japan.

Table Merck.1
Japanese Investment in Large Area LCD-Module Productions



Total investment: 3585 Mio. DM

Table Merck.2

DESIRED NEMATIC LIQUID CRYSTAL MATERIAL CHARACTERISTICS (Information supplied by Dr. B. Rieger, October 11, 1991)						
Quantity	Display Cell Type					
	TN	STN	TFT/MIM	PDLC	ECB (VAN)	FLC
Market Share (Quantity of Material)	50%	40%	10%	—	—	—
d.Δn	0.5~1.2	~0.85	~0.5	—	1.0~1.4	—
Δn	0.1~0.16	0.12~0.15	0.08~0.095	>0.2	0.18~0.2	0.13(?)
Pitch	~100μm	~10μm	~80μm			
Δε	5~20					
Threshold Voltage	0.9~1.8V	1.2~2V	1.5~2.0V	$V_{drive} \leq 5V$	≤3.0	
Temperature Range	-40~100	-30~80 (-40) (120)	-30~100 (-40)	?		
Elastic Constants	Not Relevant	Large K Large K_{33}/K_{11}	Small K	?	$K_{33}K_{11}$ Large	
Viscosity (cSt)	20~30	16~23	15~23	>20	25	
Resistivity	$10^{11}\Omega\text{-cm}$	$10^{12}\Omega\text{-cm}$	$10^{13}\Omega\text{-cm}$			
Pretilt	~1°	~5°	2°~3°		90°	Several Degrees
d	8~10μm	5~7μm	6~7μm	10μm	6μm	

REFERENCES

1. "Characterizations of Liquid Crystal Displays," prepared by Dr. B. Rieger, October 11, 1991.
2. "Japanese Investment in Large Area LCD-Module Productions."
3. *Merck Annual Report 1990.*
4. Merck Japan Limited Brochure.
5. *Merck Ag Zug Annual Report 1990.*

Site: **MITI**

Date Visited: October 2, 1991

Report Author: M. Slusarczuk

ATTENDEES

JTEC:

Credelle
Covert
Doane
Firester
Hoffman
Larimer
Shelton
Slusarczuk
Thompson
Uyehara

HOST:

Nobuhiro Miyake Discussion leader, formerly of the Finance Ministry
Junya Nishimoto
Harumitsu Suzuki

MITI is organized into eleven bureaus plus some external agencies. The bureau applicable to flat-panel displays is the Machines and Information Industries Bureau. This bureau includes machinery industries as well as information industries. It has more than 200 persons.

The industrial electronics division includes computers, communication, medical electronics, and semiconductor components. This division has an interest in FPDs. Nishimoto is in charge of the FPD area, with Suzuki as his assistant.

MITI supports Japanese R&D by helping to define and support:

1. Large-scale national R&D projects through Agency for Industrial Science & Technology (AIST)
2. New materials projects
3. 16 national laboratories, each of which specializes in a particular area

4. Direct support to private companies through projects like the Japan Key Technology Center. These projects are supported in part by money derived from dividends on the Nippon Telegraph and Telephone stock held by the Japanese government.

The fourth category provides a new system for industry to foster consortia such as HDTEC and the Giant Technology Corporation (GTC). These consortia do research in basic generic areas. Companies send engineers/scientists to work with those from other companies in government-led groups. Companies are willing to cooperate in these efforts so long as they focus on basic generic areas. Once the technology approaches the product stage, it is further developed by the individual companies.

Eight areas that have been selected for this type of development are:

1. New materials
2. Biotechnology
3. Machinery
4. Electronics
5. Telecommunications
6. Radio-communications
7. Networking
8. Image processing

Areas 1-4 are administered by MITI, and areas 5-8 are administered by the MPT.

We also learned from Professor Kobayashi of Tokyo University of Agriculture and Technology that the project-selection process is slow and involves consensus-building. It includes senior professors from major universities (mostly from around Tokyo), leaders from industry, and government officials. Prof. Kobayashi was instrumental in establishing the Giant Electronics Group.

Site: **NEC CORPORATION**

Date Visited: October 3, 1991

Report Author: T. Credelle

ATTENDEES**JTEC:**

Credelle
Glenn
Slusarczyk

HOST:

Keiji Nunomura
Fujio Okumura
H. Katoh
Chizuka Tani
Shigehiko Satoh
Setsuo Kaneko

Our visit was to the R&D Center, which employs 1450 people (1000 scientists). NEC spends 1% of sales (\$23B in 1990) at the R&D Center; 8% overall. LCD research is part of Functional Devices Research Lab. NEC produces color LCDs, CRT, VFD, and plasma (are exiting plasma business). Most important R&D topic now is color LCD for office automation (OA). NEC PC is designed around a color screen, so color LCD is essential. NEC believes that color STN is not sufficient for market acceptance. They have developed MIM for OA, but have no plans yet to produce. NEC stopped working on ferroelectric LCDs two years ago because of manufacturing problems. Recently they started investigating PDLC for projection TV.

The main area of R&D is in a-Si TFT, but NEC is also developing MIM and p-Si TFT active matrices. NEC is also researching color plasma for large screen sizes (surface discharge AC plasma); 100 cd/m² brightness in color has been achieved.

a-SI R&D (OKUMURA)

NEC has developed a 4.3-inch 720 x 480 mono AMLCD for projection; pitch is 0.13 mm. A contrast ratio of 200:1 has been achieved with a black matrix. NEC is

investigating the relationship between surface roughness and a-Si TFT mobility. Through the use of an atomic force microscope they have optimized the deposition conditions to achieve higher mobility (1.0 vs. 0.3 for rough surfaces). The deposition speed is slow, but the critical region is only near the interface. This process would probably be used only for high-resolution projection LCDs because of the need for small devices.

Another development topic is self-aligned TFT to reduce nonuniformities caused by source--drain capacitance. A back exposure is used in a staggered bottom gate structure; an ion shower is used to dope the contact regions. Chromium silicide is formed in the contact region to achieve self-alignment. They may use this development on high-resolution LCDs.

MIM LCD

A 9.3-inch MIM LCD was described (Cr/SiNx/Cr) next. Resolution is 640 x 400, with a 0.312-mm pitch. Contrast ratio of 30:1 and 20-ms response was achieved. Recently they produced a color version with 16 gray levels and 100:1 contrast ratio (black matrix included). They claim to have solved the drift voltage problem with time and showed data of essentially no drift in 1000 hours of operation. Even though they have achieved this level of performance, they still believe that gray scale uniformity is a problem, especially in 16-level mode.

p-Si TFT

NEC has an active program in p-Si using an excimer laser remelting method. They are planning to use recrystallization. They are developing processes that work on large substrates at temperatures below 600°C. The p-Si is deposited by LPCVD and then converted in p-Si through excimer laser anneal. To reduce reverse current leakage, they are planning to use a staggered structure with an offset field to reduce high field near the channel. NEC has achieved 20 MHz shift register operation at <20V. For the future, they will try to develop gas-phase doping to eliminate the ion implant step.

OTHER DISCUSSIONS

NEC estimates that the cost breakdown of OA-size LCDs is 1/3 TFT and 1/3 panel assembly. This is the main reason for the p-Si program. A main application at first is projection TV. They have built a 4.3-inch a-Si TFT LCD but plan to switch to p-Si "in the near future." The aperture ratio for 50- μ m pitch (HDTV) is approximately 30%.

NEC now mass-produces about 10,000 a-Si TFT LCDs/month at a plant on Kyushu Island. Newspaper reports are that the yield is >60%; they did not confirm or deny this report. The factory is highly automated with robot carts to transfer cassettes from one machine to the next (operator transfers substrates manually); mother glass size is 300 mm x 350 mm.

NEC feels that there are no major research issues in a-Si. Driving methods are still being developed, and, of course, manufacturing yield improvements are being studied.

Site: **NIPPON HOSO KYOKAI (NHK)**

Date Visited: October 9, 1991

Report Author: J. Larimer

ATTENDEES**JTEC:**

Glenn
Larimer
Shelton

HOST:

Takehiro Izumi	Director General, Science and Technical Research Laboratories
Taiji Nishizawa	Deputy Director General, Science and Technical Research Laboratories
Dr. Takehiko Yoshino	Deputy Director General, Science and Technical Research Laboratories
Keiichi Shidara	Director, Image Devices Research Division, Science and Technical Research Laboratories
Dr. Hiroshi Murakami	Senior Researcher, Electron Devices Research Division, Science and Technical Research Laboratories
Dr. Takeo Suzuki	Senior Researcher, Science and Technical Research Laboratories
Masami Honda	Engineering Development Center, Engineering Administration Department

The visit began with an overview of Nippon Hoso Kyokai (NHK) presented by Mr. Izumi, Director General of the laboratory. After the introduction came discussions of the various display technologies developed and used by NHK. The primary focus of the discussion was the ongoing work on plasma display panels or PDP, but the discussion also included discussions of NHK work on polymer-dispersed liquid crystal light valves, electroluminescent flat panels, and, very briefly, HDTEC. We were given demonstrations of their 33-inch diagonal PDP, the Super-HARP Camera, and High-Vision. Following these demonstrations, discussions continued through lunch.

INTRODUCTORY COMMENTS

Nippon Hoso Kyokai, NHK, is Japan's public broadcasting corporation. The Science and Technical Laboratories were established in 1930. The mission of the laboratories is to perform "research and development required for progress in broadcasting and its reception." This mission can be subdivided into three areas: (1) "studies of putting new broadcast media into practice," (2) "studies of improved conventional broadcast services," and (3) "studies of future broadcast technology and systems."

The laboratories, located in Tokyo, have a floor space of 19,000 m² and employ a staff of 320 individuals, 270 of whom are researchers. The annual budget is ¥7.7 billion (~60 million U.S. dollars) and represents 1.3% of NHK's total budget. The laboratory has nine research divisions:

- (1) Advanced Television Systems - HDTV and digital broadcast systems
- (2) Image Devices - image devices and flat panels for HDTV
- (3) Satellite Broadcasting Systems - direct broadcast satellite (DBS), and integrated services digital broadcasting (ISDB) multiplex broadcasting
- (4) Radio Engineering - SHF technology, optical fiber transmission, reception systems
- (5) Video Engineering and Data Processing - cameras, video signal processing, machine translation
- (6) Recording and Mechanical Engineering - HDTV VTR, high-density and wide-band recording, precision machining
- (7) Auditory Science and Acoustics - audio systems and equipment, sound bit-rate reduction, PCM, speech recognition, auditory sensation
- (8) Visual Science - visual sensation, neural networks, 3DTV
- (9) Solid-State Physics and Devices - semiconductors, CCD, LSI, optoelectronics, LCD, EL, magneto-optical materials

In addition, NHK Engineering Services, NHK-ES, transfers NHK expertise and technologies to the private sector. They support and provide services for:

- (1) joint development
- (2) system design and consultation

- (3) new technology applications
- (4) technical cooperation
- (5) architectural acoustic design
- (6) patents and utility model rights
- (7) technical seminars
- (8) international symposia

Some of the companies and organizations that participate with NHK in joint development and/or cooperate in holding an exhibition are All Nippon Airways, Matsushita Electrical Industrial, Oki Electric Industry, Sanyo Electric, Canon, Hitachi Chemicals, Hitachi Denshi, Mitsubishi Electric, NEC, Nippon Steel Corp., Sony, Sumitomo Electric, Toshiba, JVC, Yamaha, Astrodesign, Toppan Printing, Leader Electronics, Shima Seiki, the Broadcasting Technology Association, Mietec, Seiko-Epson, and the Railway Technology Research Institute. This list was taken from "NHK Technology Open House at NAB '91" and is not exhaustive.

Recent research areas include satellite broadcast transmitters, shaped beam antennas, mobile receivers for DBS, digital DBS systems, large flat-panel display technology for HDTV, large-scale integration (LSI) for television receivers, compact and lightweight charged coupled device (CCD) cameras, wireless cameras for real-time broadcast systems, low-light extremely sensitive cameras based on high-gain avalanche rushing amorphous photoconductor (HARP), high-quality sound synthesizing, digital VTR cameras and editors with a 1/2-inch tape format, FM multiplex broadcasting for mobile and portable reception and display systems, optical cable television, 3D television with and without glasses, super surround audio, machine-based natural language translation, and surface recovery from multiple-look data using neural networks.

FLAT PANEL DISPLAYS

On the basis of a series of experiments (Hatada, Sakata, & Kusaka, 1980), NHK believes that large screen areas are required to evoke the sensation of realism in telecommunications. To achieve the goal of realism, NHK has been developing large flat-panel display devices that will ultimately be larger, thinner, and lighter than current CRT technologies. We were shown two plasma display panels (PDPs) developed at the NHK laboratories in conjunction with several Japanese companies. We also discussed a small full-color electroluminescent panel and a polymer-dispersed liquid crystal light-valve projector.

The largest PDP we were shown has a 33-inch diagonal with a 4 by 5 aspect ratio. The panel size and aspect ratio were selected because of a limitation on the active printing area of the thick-film printer installed for the project. Subjectively the device had good color and motion rendering, although the image content was very limited.

It would have been informative to see a high-contrast moving target on a uniform background, but this image sequence was not available at the demonstration.

A paper by Murakami et al. (Ref. 5) describing the device stated that there were 800 by 1024 cells arranged in a quad RGBG pattern. The two green picture elements within each quad RGBG pixel reproduce independent information that corresponds to the information in the scene at the corresponding point on the screen. Thus the screen image has twice the resolution of the red or blue image. The scene sampling pattern of the images is also somewhat different due to the RGBG pixel geometry. There are 400 by 512 RGBG pixels; however, because of the independence of the two green subelements the spatial resolution is greater than 400 by 512. Gray scale was reported to be 256 levels per cell. The peak white luminance was reported to be 20 ft-lamberts. The display we saw subjectively appeared to have an average luminance value of around 6 ft-lamberts. A thick-film printing technique was used to manufacture the panel. Once perfected, this type of manufacturing should be relatively simple and potentially inexpensive. The 25-inch diagonal PDP that we were shown had excellent contrast and brightness.

A low-resolution 2.5-inch electroluminescent panel was also discussed. We were given a paper by Tsuchiya et al. (Ref. 4) that appeared in ITEC '91 and described that display. Finally, a polymer-dispersed liquid crystal light-valve projector was discussed. This was a three-color separation projector system similar in optical design to the GE light valve. The PDLC is addressed by a write light that scans the image plane, changing the light-scattering characteristic of the PDLC. A paper by Takizawa, Kikuchi, and Fujikake that described this device appeared in the SID '91 Digest (Ref. 3).

SUPER-HARP CAMERA AND HI-VISION DEMONSTRATION

We were given a demonstration of an NTSC camera, an extraordinarily sensitive camera with 2/3-inch HARP tubes that use the avalanche multiplication principle. We also saw a hi-vision demonstration of a recent full solar eclipse photographed through a telescope using an HDTV camera with 1-inch HARP tubes. The camera's performance in sensitivity and spatial resolution, combined with the high-resolution wide-screen hi-vision CRT display, made an extremely impressive and remarkable demonstration.

SUMMARY

Flat-panel technologies will play an important role in the broadcast television of the future. The types of information that will be available through broadcast media will increase in the future, and the distribution of service will also increase. Television

will be available in public transportation systems such as buses, trains, and airplanes. Our hosts predicted that large, thin, and lightweight plasma display panels will be in the marketplace by the end of the decade. At a future date LCD technology will be used for direct-view midsize television. LCD projectors will also be used in future television systems.

NHK will aid these trends by codeveloping with private industry many of these technologies. It also cooperates with university students by providing work/study experiences in its laboratories and by providing technology and fabrication facilities not otherwise available to them. NHK does not directly provide monetary support for university-based research. Government-sponsored consortia such as HDTEC and Giant Electronics Technology Corporation also help to develop new enabling technologies.

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Site: **NIPPON ELECTRIC GLASS**

Date Visited: October 8, 1991

Report Author: R.D. Shelton

ATTENDEES

JTEC:

Glenn
Firester
Thompson
Shelton

HOST:

Masamichi Wada	Senior Vice President and Corporate Technical Director
Takao Sakamoto	General Manager, Technical Division
Takuhiro Onoda	Engineer, Technical Division

NARRATIVE OF ACTIVITIES

Mr. Sakamoto took us to the Nippon Electric Glass (NEG) offices in Otsu by car. Most of the visit consisted of discussions in a conference room. A company video showed NEG's glass manufacturing methods and applications of many of their products. Since the discussion ended 30 minutes earlier than scheduled, Mr. Wada provided an impromptu tour of the physical testing lab.

COMPANY PROFILE

NEG is affiliated with NEC, which owns 40% of its stock. Its sales were ¥203.1 billion in FY 1990, up slightly from ¥194.6 billion the previous year. In addition to some glass-building materials, it makes a wide range of glass-related products for the electric and electronic industries: fluorescent light tubes, lenses for LEDs, windows for EPROMs, ceramic IC packages, bulbs for CRT displays, precision sheet glass for LCD displays, and many others. Of its 4,610 employees, only about 70 are engaged in corporate research and development--NEG has no central research facility. They have plants in Fujisawa, Shiga-Takasuki, Notogawa, and the one we visited in Otsu, near Nara.

SIGNIFICANT FINDINGS

The discussion centered on glass products for displays. In 1984, NEG pioneered large CRT bottles at the request of Sony. They presently are the world leader in large CRT bottles, and they make the largest--a 45-inch diagonal giant we saw in their display at the Japan Electronics Show. Mr. Wada believes that the CRT business will continue to be profitable for them because of the advent of HDTV.

However, the main product of interest to this panel was NEG's OA-2 alkali-free sheet glass intended for the substrate of active matrix LCDs. Corning's 7059 glass, which is being used by most of the display manufacturers the panel visited, has about 90% of this market. NEG is attempting to increase its market share by specifying OA-2 with a slightly higher strain-point temperature: 635°C, compared to 590°C for 7059. They also claim that OA-2 has somewhat fewer defects than the Corning glass. Mr. Wada said that Corning has recently raised its prices, and that should help NEG. He also said that NEG had sufficient manufacturing capacity to supply a much greater market share.

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3. Masamichi Wada, "New Glass Products by New Forming Technologies," (English). NEG internal publication. Engineering details of redrawing--reheating and redrawing of preform mother glass to reduce viscosity and improve dimensional precision. NEG was the first to use redrawing to make sheet glass as large as 300mm x 350mm x 0.7mm for LCD panels. The redrawing technique is used for OA-2 and other much thinner sheet glass. The temperature parameters for OA-2 given in this paper are slightly lower than the ones on the specification sheet.
4. "Electronic Glass Materials: Thin Sheet Glasses and Micro Rods," Second Edition (English) NEG 1991. Specification sheets for glass products for several display and sensor applications.

Site: **NIPPON TELEGRAPH AND TELEPHONE CORPORATION**

Date Visited: October 4, 1991

Report Author: J. Larimer

ATTENDEES

JTEC:

Doane
Larimer
Slusarczuk
Tannas

HOST:

Tadamichi Kawada Executive Manager, Technology Enterprise Promotion Section,
NTT Interdisciplinary Research Laboratories

Shigenobu Sakai Image Devices Research Group Leader, Senior Research
Engineer, Supervisor, Electron Devices Laboratory, NTT
Interdisciplinary Research Laboratories

Tadaaki Masumori Senior Research Engineer, Supervisor, Image Devices Research
Group, Electron Devices Laboratory, NTT
Interdisciplinary Research Laboratories

We were met by Mr. Kawada and taken to a laboratory area, where we were joined by Mr. Sakai and Mr. Masumori. We were shown a teleconferencing system and a 15-inch diagonal high-resolution AMLCD and were given lunch in the company dining facilities. Discussions took place during the entire period.

THE TELECONFERENCING SYSTEM

The teleconferencing system consisted of several individual stations situated around a conference table. The system we saw had five stations, but the number of stations is not likely to be a limitation. An individual station consisted of a 9.5-inch diagonal AMLCD display and a data input device. The master station included a 9.5-inch diagonal AMLCD overhead projector and a computer keyboard and monitor. All stations were networked to the PC-type workstation at the master station. The system included voice teleconferencing. These components constitute a node on a teleconferencing network.

The system did not include direct televisual communications capable of conveying real-time images of the conference participants. Visuals such as graphs and pictures could be displayed on the individual station displays or on the overhead projector. During a teleconference, individuals at the various nodes can interactively manipulate a visual such as a graph or make database entries that are displayed visually. The nodes are connected over a 64 Kbits/second T1 line, the equivalent of 16 phone lines, with 56 Kbits/second devoted to voice and 8 Kbits/second to data.

The flat-panel displays used in the teleconferencing system were manufactured by Hosiden. The 9.5-inch diagonal display was a VGA (i.e., 640 x 480 color pixels) with a-Si TFTs and no gray scale. It has an 8-color palette formed by binary combinations of R, G, and B. The 9.5-inch diagonal overhead projector display was also made by Hosiden.

NTT showed us the teleconferencing system as an example of how it integrates technology to provide telecommunication services to customers. The research and development staff is used both to promote key enabling technologies such as flat-panel displays and to engineer systems such as the teleconferencing system. Mr. Sakai's group played a central role in developing the teleconferencing prototype system. Mr. Kawada's section, called the "Technology Enterprise Promotion Section," promotes the establishment of technology enterprises based upon NTT technologies.

15-INCH DIAGONAL HIGH-RESOLUTION DISPLAY

The flat panel that was codeveloped contains NTT proprietary technologies that now are licensed to the codevelopment partner. We were given a paper describing the two 15-inch displays, which was presented at the last EURO Display Conference.

The NTT side of the display project was under Mr. Kawada's leadership. NTT provided three specific technologies:

- (1) device fault tolerance or redundancy technology,
- (2) high speed driver technology, and
- (3) low-resistance bus line technology, primarily a material fabrication issue that affects addressing speed and therefore the ultimate size and pixel count of this and future displays.

As the manufacturing process becomes more stable and controlled, the need for the redundancy schemes will lessen and the redundancy technology (e.g., multiple TFTs per pixel) will be removed as the manufacturing yields increase. Driver technology on the AMLCD substrate is important, and compatibility with existing CRT-based systems is an important feature. The source bus lines are made in an ITO/Mo/Al

three-layer stack configuration. Aluminum bus lines often form hillocks during heat processing, so NTT had to develop a hillock-free process. They believe their bus technology will support the development of future 30-inch diagonal flat-panel AMLCDs.

The high-resolution 15-inch display has 4 bits or 16 levels of gray per pixel and can address a color space of 2^{12} , or 4096 colors. We were shown no data on the discriminability of these colors, which of course depends upon the backlight, filters, pixel geometry and aperture ratio, viewing conditions, and the human visual system. We were shown the high-resolution version of the display, and it was subjectively the best large AMLCD display we saw on the entire trip, including all the LCD displays we saw at the Japan Electronics Show. I assume that the 15-inch display shown by Hosiden at the show was the VGA version.

The VGA version has 1920 x 480 dots arranged in a stripe configuration for 640 x 480 color pixels. The drivers for this display are analog and can display full color. We did not see or discuss this version of the 15-inch display, although I believe it was the 15-inch display that Hosiden showed at the Japan Electronics Show.

The high-resolution display has 1920 x 1600 dots that are arranged into RGB triads for 1280 x 800 color pixels. The gate-line drivers are divided between the right and left sides of the display, alternating two rows from one side and the next two rows from the opposite side. The source-line drivers are divided between the top and bottom of the display, with alternating columns driven from either the top or bottom. Since a pixel triad spans two rows, addressing one row of color pixels requires addressing two lines of dots. To do this a "1 line-2 scan interlaced-drive" scheme addresses first one line of dots and then the second line. All of the lines addressed from one side of the display are scanned before the lines addressed for the opposite side are scanned; this creates an interlace similar to conventional television, but based on line pairs rather than single lines.

There are two driving modes for this display. In Mode 1, 1120 x 750 color pixels are addressed at 40 frames/second (vertical sync rates of 80 Hz). In Mode 2, 4 triads or 12 dots (two contiguous gate-line driver pairs, one from each side of the display, and three contiguous source lines) are addressed as a single color pixel. In Mode 2 the vertical sync rate and frame rate are the same at 56.4 Hz or frames/second. In Mode 2 there are 640 x 400 addressable color pixels. It was not clear whether or not the driver scheme permits individual dot addressing in Mode 2. If individual dot addressing is possible, then it would be possible to implement dithering schemes to further enhance the gray scale and therefore the image quality performance of the display in this mode.

The display we saw was connected to a PC and could accommodate several frame buffer sizes (e.g., 1024 x 760, 1120 x 750, and 640 x 400). We saw only static images,

but the Hosiden 15-inch display we saw at the Japan Electronics Show subjectively seemed to have excellent temporal performance. If these are the same displays, then one would expect the motion-rendering capabilities of the high-resolution display to also be good--but we saw no direct supporting evidence for this conclusion. Subjectively, the spatial image quality was outstanding. The display had excellent uniformity; although some pixels were out, they were difficult to spot in images with high information content. The viewing angle performance seemed very good. NTT reports a contrast loss of approximately 3 db over approximately 15 degrees of solid angle and good performance--approximately an order of magnitude contrast loss--for 50 degrees right or left and 40 degrees up and 20 degrees down.

The backlight was 26W fluorescent @ 3000 cd/m². NTT claimed a screen luminance of approximately 50 ft-lamberts or 5% efficiency, but it seemed dimmer--more like 10 or 15 ft-lamberts, which would put its efficiency at 1% or 2%. Again, there were no data on this, so this is a subjective estimate. The high-resolution display is a well-engineered device that can be easily designed into a variety of systems. It appears to have excellent compatibility with many existing frame size standards.

GENERAL COMMENTS

NTT's research role is to promote the development of enabling technologies essential to NTT's future needs. It selects technologies that Japanese companies are unwilling to develop because of the risks and difficulties these technologies impose upon the developer. NTT is often able to enter into codevelopment projects with private companies, thus ensuring that essential technologies will be available when needed.

The completion of the 15-inch displays in July of 1991 marked the end of NTT's research efforts on direct-view LCDs. Now that there are many Japanese companies working on direct-view AMLCD technology, NTT's efforts are no longer required. The next topic to be addressed by several of the individuals who worked on the 15-inch display project will be a video telephone. The goal is to develop a system capable of producing the subjective experience of presence between two speakers at different locations. It is believed that the system must provide eye contact between the speakers.

NTT enters into joint research and development efforts with other companies to develop critical technologies. One of the mechanisms that NTT used in the past to support and encourage joint efforts has been the royalty system. Royalties from codeveloped technologies were returned to the NTT technical staff to support continued R&D.

It was estimated that there are several thousand people working on and researching LCD technology within Japan. Approximately 20 manufacturing companies and an equal number of university and government labs are also working on this technology.

Mr. Kawada speculated that direct-view flat-panel displays based on a-Si TFT AMLCDs, which have now achieved 15 inches in size, will achieve 30-inch diagonal sizes in the next 10 years. Direct-view displays of 50 inches will require the development of a plasma display panel. He also speculated that for projectors, poly-Si TFTs will dominate, and they will span a projected image size of 30-200 inches. CRT projectors will also continue to be viable in this range. Near-term solutions to the image brightness problem will include dual projector systems.

We were also given two viewgraphs, one of which showed the American contributions to AMLCDs:

- (1) Graphic Control Specification, VGA, EGA,...
(IBM)
- (2) Poly-Si TFT LCD Technologies
(David Sarnoff Research Center)
- (3) Glass Substrate Fabrication (7059)
(Corning)
- (4) Step and Repeat Lithography System
(MRS)

The second viewgraph, entitled "Future Prospects of LCD Technologies," stated that "active matrix LCD will come into wide use as a high information density display within five years, after the following improvements:

Cost:	Yield enhancement/process reduction
Performance:	Larger than 10 inch, better than VGA, wider viewing angle
Reliability:	Larger backlight life
Main fields:	A-Si TFT LCD for direct-view displays (3-15 inches); poly-Si TFT LCD for projection displays (3-5 inches with circuitry)"

NTT ELECTRICAL COMMUNICATIONS LABORATORIES

A brochure described the activities of the four NTT R&D centers, with 12 laboratories distributed across the centers. The major laboratories are as follows:

- (1) Telecommunication Networks Laboratories
- (2) Network Information Systems Laboratories
- (3) Human Interface Laboratories
- (4) Communication Switching Laboratories
- (5) Transmission Systems Laboratories
- (6) Radio Communication Systems Laboratories
- (7) Software Laboratories
- (8) LSI Laboratories
- (9) Optoelectronics Laboratories
- (10) Interdisciplinary Research Laboratories
- (11) Basic Research Laboratories
- (12) Communication Science Laboratories

NTT developed an Integrated Services Digital Network, ISDN, which has been in service since 1985. NTT's broad goals are to:

- (1) provide easy access to all types of information and communication equipment,
- (2) provide access from any location, and
- (3) define the systems characteristics on the basis of patterns of usage.

They envision a triple-faced communication system that encompasses service technologies, network technologies, and basic research to support future communication systems. The following list represents R&D topics and products within these three categories.

Service Technologies

- (1) Speech recognition and production
- (2) Fast data encipherment
- (3) Knowledge base management systems
- (4) Hardware-independent network technologies
- (5) Office automation technologies

Network Technologies

- (1) Photonic switching technologies
- (2) High-speed coherent optical communication technologies for chromatic dispersion compensation

- (3) Optical frequency division multiplexing technologies
- (4) Uniplanar monolithic microwave circuit technologies
- (5) Multibeam satellite communications
- (6) Network planning support systems
- (7) The intelligent network
- (8) A synchronous transfer mode-switching technology

Basic Research

- (1) High-speed optical disk memory
- (2) Synchrotron orbital radiation x-ray lithography
- (3) Integrated laser array technology for frequency division multiplexing
- (4) LSI optical devices
- (5) Ultra-high-speed GaAs integrated circuits for optical transmission systems
- (6) Underground radar systems
- (7) Quantitative software management
- (8) Materials characterization
- (9) Velocity modulation transistors
- (10) Cell culture studies of neural networks

Site: **SANYO**
 Date Visited: October 7, 1991
 Report Author: J. Larimer

ATTENDEES

JTEC:

Doane
 Larimer
 Slusarczuk
 Uyehara

HOST:

Mashuharu Takuma	Executive Managing Director and Representative Director
Tadanobu Yamazawa	Director and General Manager, LED Division
Kenichi Narita	Manager, LCD Division, Engineering Development Department, Section 1
Noriaki Nishina	Deputy General Manager, LCD Division
Toshihiko Tanaka	Chief Engineer, Engineering Development Department, Section 2

Attendees from the Tottori Prefecture Industrial Research Institute:

Naoki Kobayashi	Chief, Commerce & Industry Guidance Section
Akira Kaneda	Staff Researcher, Applied Electronics Section
Shoji Kodani	Researcher, Applied Electronics Section

MEETING SCHEDULE

We were met Sunday evening at Tottori Airport by Professors Hiroshi Kobayashi and Shosaku Tanaka of Tottori University and were joined later that evening at our hotel by Masuharu Takuma, Tadanobu Yamazawa, and Kenichi Narita. The visit to the Sanyo factory began at 1:00 pm the next day. We first saw a video that introduced Sanyo and its product lines. Sanyo is a large electrical company that produces consumer products ranging from household kitchen appliances to advanced electronic products for office automation and home use. The Tottori facility, established in 1966, employs 3000 people and has annual sales of ¥12 billion.

THE FACTORY TOUR

The STN LCD factory that we toured is less than 1 year old. Two years of planning were required prior to construction, and construction took 1 year to complete. The first STN flat-panel display produced on the manufacturing line was assembled in August of 1991, approximately 6 months after the completion of the facility. At another site, Sanyo has an equivalent facility producing STN LCDs. A second factory at the Tottori site is in the planning phase, with display production to begin in 1993. This facility will employ MIM technology to manufacture active matrix LCDs.

The factory we toured contains 11,000 square meters of floor space. The manufacturing line is approximately 300 meters long. The majority of the line is housed in two large clean rooms, which were subdivided into smaller rooms of varying clean room classifications. Two displays are constructed on a single 300 mm x 400mm x 0.7 mm sheet of Nippon Electric Glass boric silicate glass. Two of these sheets are sandwiched to form two complete STN LCDs.

One of the two sheets of glass that form a pair of displays is coated with ITO prior to the first station of processing. It was not clear whether or not this sheet was delivered to the factory with the ITO coating or whether ITO was applied at the Tottori site. All coatings for the complementary sheet, the sheet containing the color filters, are applied at the Tottori site. The colored filters are applied to the glass in the new building. First a polymer gel is spin-coated onto the glass. This is patterned by a UV photo process. The gel is dyed red, green, or blue and then baked. The process is repeated three more times to add the two remaining colors and, last, the black matrix mask. Next, a leveling layer is spin-coated onto the glass with filters. Finally the ITO layer is applied. The sheet is then ready for the processing steps required to pattern the ITO. The dye materials and suppliers are proprietary details of the manufacturing process.

Cassettes hold 30 sheets of glass each as they proceed down the manufacturing line. The line is almost completely automated, and the cassettes are transported automatically without human intervention from station to station throughout most of the process.

Figure Sanyo.1 shows the approximate layout of the two buildings that house the STN LCD factory. The numbers correspond to the locations of various stations or phases of the manufacturing process. The first 11 stations of the manufacturing process are all contained in the new building. Station 1 is for cleaning the sheets of glass. Before the glass sheets arrive at this station, the ITO and/or colored filters have been applied. There are 10 cleaning steps, with a through-put time of 5 seconds per plate. At the second station a photo-resist coating is applied by a roller coater manufactured by DaiNippon Screen. There is an in-line bake of 10 minutes.

Three proximity printers expose the address line pattern at station 3. This step takes approximately 5-10 seconds per sheet. Development, etching, and stripping take place at stations 4, 5, and 6. The alignment layer is applied at station 7. Three lines are used to apply, bake, and rub the alignment layer. Six rubbing machines, of a design unique to Sanyo, are at station 8.

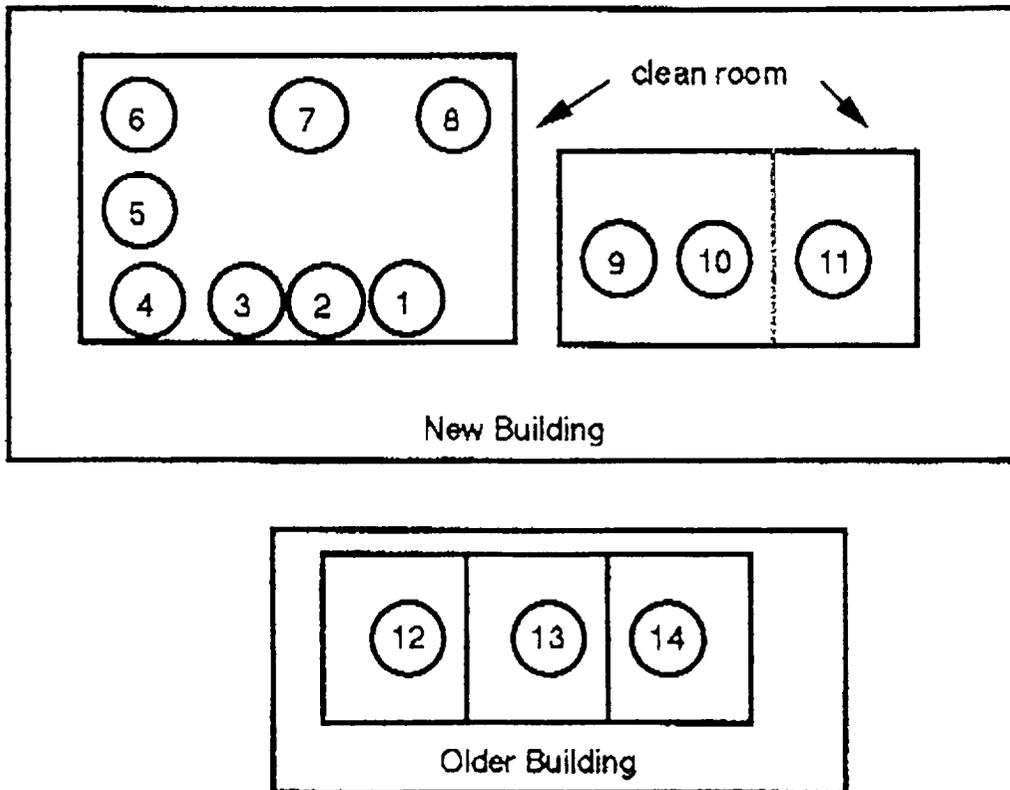


Figure Sanyo.1

The adhesive is applied to the two processed sheets of glass (one with colored filters and one without) at station 9. The adhesives are manufactured by Mitsui Toatsu Chemical. The two sheets are aligned and laminated at the next station (station 10). The spacers are sprayed on with water prior to the lamination. The cell gap is 6 microns, with a tolerance of 3%. The alignment is performed manually by an operator, but the process will be automated at a future time. Finally, the laminated sheets are cured for one hour in UV light at station 11.

The laminated plates are taken to the second building, where they are scribed on one of two manually operated Mitsubishi diamond scribe machines at station 12. In

the same area, the separation is performed by a person who breaks the two displays apart by hand. At station 13 each display is filled with liquid crystal material and sealed. Eight dual-chamber vacuum machines are used for the filling operation. The displays are filled through three holes in the adhesive layer, which are sealed and cured after filling. The final station, station 14 in figure Sanyo.1, is for inspection and packaging. The application of polarizers, retardation films, and IC drivers is done at another site 50 km from Tottori. The polarizers and retardation films are produced by Nitto Denko and Sumitomo Chemical.

The factory is operated 24 hours per day. A crew of 60 people is required to operate the facility during a single shift. We were not given data on the frequency of maintenance, cleaning, or breakdown of the factory. This factory produces approximately 150,000 displays per month.

DISCUSSION FOLLOWING TOUR

We were given a set of answers to the questions we had sent to the Sanyo team prior to our arrival. The questions and answers are included with this report. Sanyo believes that its product line in liquid crystal displays will include black-and-white STN devices and a future color MIM active matrix display device. Sanyo sees its greatest challenges as improving the contrast of both types of liquid crystal displays (STN and MIM) and improving the speed of passive STN display devices. Current problems with MIM development include unevenness in the pixel elements and a memory effect that is associated with a threshold shift in the drivers.

MIM technology was chosen for the active matrix display because it is believed to produce better manufacturing yields than TFT devices and because it is believed to be easier to adapt to FLC and PDLC materials.

Approximately 75% of the displays Sanyo produces are sold as component technology. Sanyo uses the remaining 25% in its own consumer product lines. They have not considered building displays for the aerospace industry because they see this as a low-volume, highly specialized market. Moreover, they have very little contact with this industry. Their primary market is the high-volume consumer product marketplace.

GENERAL COMMENTS

The Sanyo factory was very impressive. The staff engineers we met with were very well informed about developments in the industry. The required machine tool equipment was clearly available. Some of the factory equipment was standard, and some was specially designed for this particular factory. It is clear that Japan has a

deep infrastructure of machine tool manufacturers and component technology suppliers. The engineering staff at Tottori Sanyo clearly spans a large age range; thus a wide range of experience and expertise in research, development, and manufacturing has been tapped to develop this maturing industry. The human resources required for this industry are in place and growing in Japan.

GENERAL QUESTIONS BY THE TEAM

Liquid Crystal Displays

- Q. What size panels have been fabricated, in color and in monochrome?
A. 16.7" (1120 x 780 dots) for monochrome and 8.5" (VGA color) for simple multiplexed STN.
- Q. How can optical efficiency of panels be improved?
A. Larger twist angle and optimized liquid can improve it.
- Q. What method do you expect will improve off-axis contrast ratio?
A. Retarder film will improve it by making a z-axis retardance.
- Q. What interconnect technology do you use today? How do you plan to approach interconnects in 1995? In 2000?
A. Now we use zebra connectors, heat-pressing type conductive films and anisotropic conductive adhesive films. We don't know about the technology in the future.
- Q. What are prospects for fast-response LCDs (<100 ms) at temperatures <0°C, < -20°C?
A. AMLCD+SmC system will overcome the issue.
- Q. What, if any, R&D is being done on new LC modes to improve optical performance (viewing angle, transmission, efficiency, contrast ratio, response time)?
A. AMLCD+SmC system or AMLCD+PDLC is being studied.
- Q. What are the prospects for low-voltage polymer-dispersed LC(PDLC) with high contrast ratio?
A. We understand it is a promising system.
- Q. Will PDLCs ever be acceptable as direct-view multiplexed LCDs? If so, when and at what level of multiplexing?
A. Now the level of multiplexing is 1/3 ratio.

- Q. Are PDLCs useful for projection systems? Will they replace twisted nematic LCs? If so, when?
- A. No answer given.
- Q. What are the prospects for reducing the number of masking steps? Is a 2- or 3-mask process commercially viable?
- A. Our MIM system will overcome the issue.
- Q. Are integral drivers commercially feasible? If so, when? What is cost comparison to external drivers?
- A. Now we use fine-pitch and narrow-width TAB ICs.
Ex.: (A) 0.14 (pitch) x 160 (outs) x 11 (widths)
(B) 0.22 (pitch) x 80 (outs) x 8 (widths)
- Q. What techniques can be used for driver attachment for high-resolution LCDs (>10 pixel/m)?
- A. Now the level of 5-6 pixels/mm is obtained by anisotropic adhesion techniques.
- Q. What are the limitations of MIMs in resolution and display size?
- A. We don't know. Now we are improving the I-V characteristics rapidly.

STN LCDs

- Q. What are the size and resolution limits for STN LCD?
- A. We have already got 20:1 CR.
- Q. What are the prospects for 50 mms response times with >15:1 CR?
- A. We don't know.
- Q. What techniques can be used to improve viewing angle?
- A. It can be improved by giving a retardance to z-axis of compensation film.
- Q. What are the prospects for wide temp range (-40 to 70°C) with usable CR(>5:1)?
- A. No answer given.
- Q. What is being done about cross-talk?
- A. As one of measures, some scanning lines are driven from both sides of the LCD panel. This can improve contrast, too.
- Q. What techniques are under development to reduce costs?
- A. To improve the quality of manufacturing facilities and enhance the yield is the first thing to do.

- Q. When will STN be replaced by AMLCD, if at all?
A. We don't think STN market will be replaced by AMLCD.
- Q. What are prospects for color STN LCD with >15:1 CR? What response time is feasible?
A. Now we can offer 350 ms (Tr + Tf).
- Q. What breakthroughs are needed to advance the performance of STN LCD?
A. No answer given.

Ferroelectric LCDs

- Q. What are the main research topics in FE LCDs?
A. The *Nikkei Sangyo* newspaper of October 1 reported that Hitachi and Takeda Pharmacy had developed a 3.68-million pixel, 3.3" screen with response <200 ms/picture.
- Q. What are prospects for increasing temperature range to 0-50°C? To -40-70°C?
A. We don't know the recent technological trend about FE LCDs.

Backlights

- Q. What backlight technology do you see as most suitable for AMLCD laptops? Portable TV on the wall?
A. No answer given.
- Q. What novel research in backlight technology do you see as most promising? For example, RF fluorescent, electroluminescent, color sequential cold cathode, etc.
A. No answer given.
- Q. What are the parameters, brightness, lumens per watt, power consumption, spectral distribution, size, thickness, lifetime today? In the year 1995? In 2000? What are the limiting issues? What R&D is conducted to address these issues?
A. No answer given.

LC Materials

- Q. What is the most critical LC material problem from the perspective of AM design and processing?
A. High-level resistivity and electrochemical stability are the most important.

- Q. What level of interest is there in non-STN or non-TN materials? For example, VAN, PDLC, SmC, ferroelectric?
- A. PDLC > SmC > VAN
- Q. What materials cause the most limitations in your display products?
- A. We consider that defects in the alignment layer limit the yield.
- Q. What are the technical tradeoffs of the major approaches to color filters for LD, and what are the new developments?
- A. We are now trying to get the pigment-dispersed photo resist for easy mass production.

Alignment Layers

- Q. What qualities do you believe the alignment layer should have to reduce the effects of ions in the display (like image sticking)?
- A. It should have volume resistivity.
- Q. Is there a need for low-resistivity alignment layers because of the ion problem? If so, how are plate-to-plate shorts avoided?
- A. No answer given.
- Q. What is the best pre-tilt angle for STN devices? How can this high pre-tilt be achieved?
- A. It can be achieved by designing special molecular structures of alignment polymer.
- Q. What characteristics of alignment layers are desirable for new devices such as VAN and SmC? What research will lead to these characteristics?
- A. We don't know.

ITO Layers

- Q. What resistivity will be required for future passive matrix displays? For video rate STN and SmC devices?
- A. We hope to get under 5 Ω /sq.
- Q. What can be done to minimize the plate-to-plate shorting?
- A. It can be minimized by decreasing particles in every facility.

Site: **SEIKO-EPSON**
Date Visited: October 5, 1991
Report Author: A. Firester

ATTENDEES

JTEC:

Covert
Firester
Glenn
Hoffman

HOST:

Hiroshi Harigaya	Director, Corporate General Manager Corporate Research & Development
Mitsuru Kono	General Manager of R&D Planning R&D Division
Kanemitsu Kubota	Manager, Display Technology Laboratory R&D Division
Hiroyuki Ohshima	Manager, TFT Research Laboratory Corporate R&D
Hiroshi Takayama	Manager, Sales and Marketing Section TFT/MIM Division
Nobuyoshi Takei	Manager, LD Overseas Sales Section LCD Division

AGENDA

Mr. Takei graciously acted as our escort on our trip to and from Seiko. We arrived at about 10:00 a.m. and left about 3:45 p.m.. The meeting was hosted by Mr. Kono. An outline of our meeting follows.

1. Greeting - Koyama
2. JTEC introduction - Glenn
3. Product demonstrations - Kono
p-Si projector and camcorder viewfinder, MIM pocket TV, and color VGA display
4. Seiko-Epson SPN Technology - Ohshima and Kubota
5. Lunch - Harigaya
6. Sarnoff p-Si status - Firester
7. Technical discussions - All

BACKGROUND

Seiko-Epson is a privately held company in the Seiko Group. The four companies in the Seiko Group are shown in Table Seiko.1 with their principal products.

Table Seiko.1

<u>Company</u>	<u>Principal Product</u>
Hattori Seiko Co. Ltd.	trading company
Seikosha Co. Ltd	clocks
Seiko Instruments, Inc.	watches
Seiko-Epson Corp.	watches, computers and components

Company statistics provided by Mr. Koyama are as follows:

Head office -	Suwa-Shi, Nagano-Ken
Employees -	12,600 (9/90)
Capitalization -	\$80 million
Annual sales -	\$3,100 million

(All \$1 = ¥ 150)

Large-size module '91 projected market

Total: ¥100,000 million

Epson -	20%
Sharp -	30%
Sanyo -	15%
Toshiba -	10%
Hitachi -	10%
Others -	15%

TECHNOLOGY

- p-Si
- MIM
- Projection
- Other
- CF, FELC, PDLC

PLANS AND STRATEGY

Although Seiko-Epson was first to market with a silicon chip wrist TV in 1982 and a p-Si pocket TV in 1984, they discontinued their p-Si pocket TV products in 1986 and switched to MIM as the active matrix technology for their pocket TVs. Their current plans are to pursue p-Si active matrix for small, ≤ 2 -inch diagonal products such as projection light valves and camcorder viewfinders. Larger display applications, both personal TVs and office automation equipment, will use MIM active matrix

technology. Seiko is convinced that they can compete with a-Si TFT technology for large-size displays with equal performance but substantially lower costs.

Seiko has been a supplier of specialized p-Si displays for avionic applications with sizes as large as 96 mm x 88 mm. They will continue to fulfill their contractual commitments but do not intend to expand either in display size or avionic market penetration.

TECHNICAL DISCUSSIONS

p-Si

Seiko uses a high-temperature (HT) p-Si process on quartz substrates. There is ongoing research to develop a low-temperature poly process that would permit the use of glass substrates. The products they currently produce using the HT p-Si process are as follows:

- (a) Viewfinder (OEM)
 - 0.7" diagonals
 - 320 x 220 TFTs*
 - Delta color pattern
 - Used in Fugix Handycam

*A higher resolution model, with 50% more TFTs, is also planned.
- (b) Projection light valve (internal use only)
 - 1.32-inch diagonal
 - 480 x 440 TFTs
 - Integrated analog drives
 - $T_r + T_f = 50$ msec
 - Used in Seiko Projector VPJ - 2000

The basic LV is denoted EF01. It has integrated drivers and has approximately 25 leads. The integrated drives are located *outside* the LC seal area in order to prevent LC degradation by the dc voltages used in the drive circuitry.

- (c) Special avionics displays

These are special displays built under contract to a U.S. company. One is a 3ATI display for a TCAS (traffic collision avoidance system), and the other is a 96 mm x 88 mm monochrome display for avionic data applications. These displays will be produced as per the customer contract, but no further production of special-purpose avionic displays is desired or planned. Epson plans to focus on viewfinders and projection light valves.

No expansion of Seiko's p-Si production facility is planned. Their current size capability is limited to about 5" x 4.5", and no size capability increase is planned.

MIM

Seiko has decided that the MIM technology will be their approach for TV and OA applications requiring AMLCDs larger than 2-inch diagonal. MIM active matrices will have performance equivalent to a-Si TFT active matrices at very much lower manufacturing costs. They are continuing their MIM research. The advances they seek are reduced capacitance and reduced leakage (cause of cross-talk). Current MIM products are described in Seiko's brochure and summarized in Table Seiko.2.

Table Seiko.2
Current MIM Products

Type	Size (diagonal inches)	Pixels	Pixel/Pitch (μm)	Mode
LF9VG	9.0	(640x3) x 480	(95x3) x 285	RGB Vertical Stripe
LF9PC	8.9	(640x3) x 400	(100x3) x 300	RGB Vertical Stripe
LF5	5.3	634 x 238	168 x 335	RGB Diagonal Stripe
LF4	4	610 x 230	136 x 264	RGB Diagonal Stripe
LF3	3.3	442 x 238	146 x 208	RGB Diagonal Stripe
LF2	2.6	312 x 238	164 x 167	RGB Delta

For these color products, Seiko produces its own color filters. For the 9V color PC display, this filter is on top of the ITO stripes, thereby reducing the voltage across the LC and resulting in a narrow viewing angle. In the TV displays, the ITO is on top of the color filter, thereby providing maximum voltage across the LC material and resulting in a wide viewing angle. Another distinction between the 9-inch PC unit and the 4-inch TV unit is that the former operates in the normally black mode and the latter in the normally white mode.

Projection

Seiko is producing a p-Si AM light-valve projector - Model VPJ-2000. Light-valve transmission is ~15% (polarizers ~40% and aperture ratio ~40%). The unit uses a

150-Watt metal halide lamp and provides 70 lumens output. (See section on p-Si for light-valve specifications. According to Seiko, if lamp power were increased to increase the light output, then the increase in light-valve temperature would limit the maximum output. Specific details on light absorption were not provided.

Other LC R&D

- o Response time of Seiko STN panels is $T_r + T_f = 100 + 100 = 200$ msec.
- o Seiko has solved the FLC stability problem using antiferroelectric LC and a new orientation layer. This requires 30 volts drive for a 1000-line display. 640 x 480 is realizable but costly because of 2 mm gap requirement.
- o Seiko also uses p-Si TFTs with a-Si photoconductor for linear sensor products for fax machines. There was no detailed discussion of this product.

DEMONSTRATION

We were given four demonstrations:

1. LC projection
Double-line progressive scan at 60 Hz
50 msec $-T_r = T_f$ (10% to 90%)
Good uniformity
Needed gamma correction in highlights
2. 9V MIM color display in a notebook PC
(3 x 640) x 400
Viewing angle: ± 40 - 50° horizontal
 ± 20 , -15° vertical

Both horizontal and vertical cross-talk were clearly visible.

$T_r = 40$ msec

$T_f = 30$ msec

3. 4-inch diagonal MIM TV
Viewing angle: $\pm 60^\circ$ horizontal
 $\pm 20^\circ$ vertical
16-level gray scale drivers; manufactured by Seiko Response, same as (2) above.
4. Fugix Handycam containing 0.7" color viewfinder. Quite nice; coarse pixelation.

Site: **SHARP**

Date Visited: October 7, 1991

Report Author: W.E. Glenn

ATTENDEES

JTEC:

Firester
Glenn
Shelton
Thompson

HOST:

Mitsuo Ishii	Division Deputy General Manager, Liquid Crystal Research Laboratories
Masataka Matsuura	Dept. General Manager, Liquid Crystal Research Laboratories
Yasukazu Mori	Manager, Foreign Trade Relations Department
Hiro Kawamoto	Department General Manager, Corporate Staffs-Planning and Development
Yutaka Takafuji	Chief, A1164 Project Team
Hiroshi Morimoto	Dept. General Manager, Engineering Development, Liquid Crystal Research Laboratories
Mr. Kawamoto	Acted as a coordinator and interpreter for the meeting

Sharp has a worldwide business of over \$10 billion, of which the Liquid Crystal Display Group represents about \$1 billion in sales per year. This is about one third of the worldwide market for LCDs. Sharp spends about 8% of sales revenues on R&D and has a total R&D staff of 7300 people. An article in *Business Week*, April 29, 1991, gives more details of their history.

The 14-inch display is the largest Sharp produces. All active matrix panels in production use amorphous silicon on Corning 7059 substrate.

Their total LC production had about 25% AMLCD in 1991, but the percentage is growing rapidly.

Sharp will soon complete a new, very large, seven-story building that will be devoted entirely to TFT production. They feel that Toshiba is their closest competition. As for major production problems for amorphous silicon, they felt that throughput and yield were the major problems. Electrostatic damage was also a major yield problem.

In its research activities, Sharp is studying polysilicon. They find it attractive as a way to incorporate the drivers on the panel. Work is being done on low-temperature polysilicon (<600°) so that glass could be used as a substrate. This should reduce the cost and improve reliability and panel shrinkage. Laser recrystallization is one of the techniques being studied to give a low-temperature process.

Research is being done on color filters. At present Sharp buys some of its color filters, drivers, backlights, and arc lights from other companies. They are working on PDLC, FELC, and ECB because of their possible wider viewing angle. They think FELC will be a good candidate for high-resolution computer displays where gray scale and speed are not required.

The Sharp high-definition LCD projectors at the Japan Electronics Show demonstrated excellent image quality. However, the television people responsible for its development were not at our meeting. The people in attendance could not answer most of our questions on it.

For the future, Sharp feels that a-Si panels can be made in XGA format up to about 20". They feel that 40 cm x 40 cm is about the largest substrate that can be manufactured at a reasonable cost. They don't believe STN is a direct competitor, since AMLCD gives a better image. As for production plans--they hope to have 14" XGA panels in production by 1995.

In the future Sharp expects EL panels to compare favorably with AMLCD because they have a wider viewing angle and are easier on the eyes. Sharp expects LCD panels to exceed production of CRT displays below 14" in about 1995. From 16" to 39", they feel that CRT will still dominate for the next decade or more. Above 39", they expect the AMLCD projector to dominate.

The U.S. office of Sharp is:

Sharp Electronics Corporation
Microelectronics Group
5700 Northwest, Pacific Rim Blvd - Suite 20
Camas, WA 98607, U.S.A.
Phone: (206) 834-2500
FAX: (206) 834-8903

REFERENCES

1. *Sharp Electronic Components* - October 1991. This is their catalog of electronic components Ref# HT 915D.
2. *Sharp Flat Panel Displays LCD Units/EL Display Units*. This is a catalog with detailed technical specifications, Ref#HT 518D.
3. *LCD Displays - The leading Edge in Flat Panel Displays*. This is a tutorial on LCD panels - their principle of operation and their commercial uses.
4. "Sharp's Long-Range Gamble on its Innovation Machine". *Business Week*, April 29, 1991.

Site: **SHARP FACTORIES (Tenri & Nara)**
 Date Visited: October 9, 1991
 Report Author: J. Covert

ATTENDEES

JTEC:

Covert
 Hoffman
 Slusarczuk
 Tannas

HOSTS:

SHARP (Tenri):

Minoru Fukuoka	Group General Manager, LCD Group
Yasunori Nishimura	Deputy Head, A1153 Project Team, LCD Group
Hiroshi Take	General Manager, 2nd Product & Planning Dept, LCD Group
Jyunichi Matsuda	General Manager, Foreign Trade Relations Dept., International Business Group
Yasukazu Mori	Manager, Foreign Trade Relations Dept, International Business Group

SHARP (Nara):

Hisaaki Nakajima	Plant General Manager of Nara, LCD Group
Etsuo Mizukami	Manager, Products Planning Dept, LCD Group
Hideo Isozaki	Manager, Products Planning Dept, LCD Group
Hiromu Watanabe	Department General Manager, Engineering Dept 1, Duty Panel Development Center, LCD Group
Toshio Wakatsuki	Department General Manager, Production Engineering Dept, LCD Group
Yukihiko Inoue	Department General Manager, Engineering Dept 2, Duty Panel Development Center, LCD Group

Sharp was founded in 1912. They marked their 79th year of business in 1991, with 31 manufacturing plants in 23 countries. Their first product was the Ever-Sharp

Pencil (invented by founder Tokuji Hayakawa), from which the company name and trademark are derived. Products include business equipment (computers, etc.), personal equipment (calculators, organizers, etc.), optoelectronics (TFT LCD, LED, EL display, etc.), commodity distribution systems, measuring and control equipment, manufacturing systems, TV/video, audio, air conditioning, kitchen appliances, home products, integrated circuits, and general components (thin-film sensors, tuners, etc.).

TENRI VISIT

The Sharp Tenri factory produces only TFT LCDs using a-Si. We were the first foreign group ever to see this new facility. The building, completed in February 1991, has a total floor area of 36,000 sq meters (83 m W x 87 m L x 31 m H), with production planned in one half of this area. The building took two years to design, and six months was planned for installation of equipment. At the time of the JTEC panel's visit, clean room equipment was being installed, and initial production was planned for January 1992. Their existing plant at this site is a 6,000 sq meter facility; 65% of this area is in production, currently making 70,000 TFT LCDs per month. By March 1992, when the new facility became operational, this facility was capable of producing 120,000 displays per month. About 1,000 people, of whom 60% are production workers, are working TFT LCD production at this facility.

Sharp's a-Si TFT 3- μ m design rule process was described as using five masks for TFT fabrication and two for passivation and terminals. Test of a single transistor per panel on sample (not all) panels is used to characterize panel yield. Sharp buys its color filters from outside vendor(s). Tenri fabricates the TFT substrate and assembles the glass panel using automatic alignment techniques. The glass panel is tested before drivers are attached. Other subcontractor facilities assemble the electronics. Anisotropic adhesive is used to attach drivers.

Tenri builds the following TFT LCD products as shown in Table Sharp.1. Detailed specifications are attached for some products. They supply various modules to outside customers.

The new clean room facility we toured was undergoing final assembly of clean room equipment. The building floor-to-floor height was 8 meters, with 3.5-meter room height. A 40,000 panel/month production rate is planned similar to the 50,000 per month indicated earlier in our discussions. It appears that two more facilities like this can be repeated on two more floors.

Table Sharp.1
Tenri's TFT LCD Products

<u>Size (diag)</u>	<u>Row & column</u>	<u>Subpixel</u>	<u>Use</u>
3 in	234 x 382	29,835	Hand-held TV
4 in	234 x 479	37,440	Hand-held TV
5.7 in	240 x 720	57,600	Automotive
8.4 in	480 x 640 (x3)		Computer
8.6 in	456 x 960	145,920	Video Display
10.4 in	480 x 640 (x3)		Computer

The CVD and sputtering equipment were all located in a class 100 area, and all appeared to be Anelva equipment we saw later in our visit to Anelva on October 11, 1991. The CVD equipment appeared to be with substrates starting at the Clean/Etch end of the line and being returned from the far end of the CVD line by robots on tracks to reenter the Clean/Etch area through a load-lock. Sputtering equipment was being installed. A 20- (or more) panel cassette was seen in the Clean/Etch area, but it was difficult to judge the substrate size. Our notes from this visit indicated that the next size, 500 mm x 550 mm, would take 4-5 years.

We also visited the basement area, where gasses were handled. We saw three recovery tanks. The area is huge by Japanese standards and can accommodate trucks for handling of materials. Nitrogen is made on site, but other materials are delivered. Thermal shock ESPEC, reliability, environmental, temperature, and vibration testing capability is in the basement. The facility is currently operating around the clock.

Concerning plans for substrate size, it was indicated that internally Sharp does not agree on its approach. Our hosts suggested that two approaches should be used: For small products, smaller mother glass should be used; and for workstation sizes, mother glass larger than 10 inches should be used.

It was indicated that the useful life of the machinery was 3-5 years. Equipment is depreciated over 5-6 years, consistent with equipment life. Plans are to build 3-inch displays in the old plant and all larger displays in the new plant. Sharp plans to build new lines every 2 years and insert new technology. Their experience in building plants is that it takes 1 year to complete the plant, 6 months to install equipment, and 1 year to achieve design yield, with the learning curve depending on the size of display. Updating/engineering of equipment for a new plant is mostly done by Sharp, not by the equipment manufacturer. They mature a new process in their old facility before establishing a new facility. Production workers come straight from high school, and learn the job in the plant through team training. There is no

formal training to learn this business. Our hosts indicated that the morale in the LCD Group is the highest in all of Sharp. They have dorms at Tenri for the production facility.

Sharp is planning for passive matrix LCD assembly in the United States, and, if this works out, it may be possible to build display manufacturing capability in the United States.

Sharp is doing p-Si research and is interested in both high- and low-temperature processes. They do not believe p-Si will be important for large displays. They believe that the cost of external drivers is lower than that of integrated p-Si drivers. They indicate that p-Si drivers cannot match Sharp's driver performance. They currently use 20 mHz analog drivers. When asked to compare TFT and MIM LCDs, they indicated that several requirements of MIM cell thickness, resistivity, and capacitance would limit application of MIMs.

When asked about their plans for producing cockpit displays, they indicated that on a commercial basis they need more than 5,000 displays per month for 2 years of a single design to produce such a display. They currently build auto displays with specification of -30 to +80°C for storage and -10 to +70°C for operation, and are planning to develop modules with -30 to +80°C operational capability. At temperatures around -55°C, LC crystallization is a problem.

NARA VISIT

Four LCD production lines are operational at Nara (only two are open to outsiders), producing TN and STN displays. Sharp's long history in displays was presented in detail. Their monthly production capacity of TN LCDs for calculators and measuring instruments etc. is 10 million, and that of STN LCDs for graphics displays is 350 thousand and that of EL displays, mostly for machine control, is 12 thousand pieces. A total of 300 people do LCD production in four groups and three shifts around the clock. LCD 1 A & B lines are on the first floor. Line 1 B was added this summer with emphasis on speed and economy of process. The LCD 2 and LCD 3 lines are on the second floor. A line is chosen for production on the basis of customer needs.

The LCD2 line we saw was 10 years old, and was updated last year. It is a TN display line that produces 10 million small displays per month for calculators. It uses 300 x 320 mm substrates. Humidity control is the primary control for static, and control techniques are used at each stage. Hot press is done for 10 minutes to set the seal and to control cell gap. Scribe and break are fully automated. There was some automatic inspection after exposure, but they indicated it was used only to tune the run and not needed later. Batch cassette-to-cassette with manual machine-to-machine transfer was used. Our hosts indicated that this was the same for the

other lines as well. Equipment is cleaned every day, with fixed-time maintenance every 2 months.

Yield is top secret because it determines profit and cost of product, but it is about 80-90% overall. Yields are about the same for EL. The STN lines at Nara usually don't do repair. Resist was put on with rollers, and uniformity was the main issue for yield. It has taken about 6 months to 1 year to reach design yield for STN.

Experience has shown that many problems must be solved for each step in the process. Total Productive Maintenance (TPM), a management method, is used by all Nara people to improve yield. Fifty teams have been in place for 3 years, with one more year planned in this cycle. Engineering and management meet with the TPM teams once per month to understand their activities. Sharp works with its own precision machine company as well as other manufacturers to design new machines for display production. New machines are debugged on an existing line before a new line is built.

We received detailed specifications for Sharp Nara's new STN 640 x 480 display. Sharp started in the EL business in 1983, and growth was flat until 2 years ago when it jumped to 50%/year with expansion of the equipment controller market. They believe EL can continue at the 50% growth rate. They believe EL and plasma will coexist, and both will experience a 50% growth rate. "Full-color EL is a dream for Sharp." Use of a color filter is a possible solution. Yellow source with red or green filter could enable red and green operation. Blue emission efficiency is a problem. Sharp is working on blue phosphor at its Central Research Laboratory. They indicated that a 1024 x 1280 dots EL display was demonstrated at the Japan Electronics Show in 1991.

Site: **SHARP SHOWROOM**

Date Visited: October 3, 1991

Report Author: L.E. Tannas, Jr.

ATTENDEES

JTEC:

Credelle
Doane
Glenn
Doane
Slusarczuk
Tannas
Uyehara

HOST:

Professor Uchiike

Professor Uchiike of Hiroshima University took a group of JTEC committee members on a tour of the Sharp Showroom located near Ichigaya Station, west of Central Tokyo on the Chuo Line.

The main feature of the showroom was the Sharp HDTV using an a-Si TFT LCD projector. The image was exceptionally good. There was less than one-half pixel misconvergence in the RGB color.

Sharp showed all the LCD sizes in exhibits emphasizing the flatness, size, resolution, and color advantages. The major product sizes and applications are shown on the following pages, figures Showroom.1-Showroom.4, taken from Sharp-provided literature.

The price of the a-Si TFT LCD projectors started at approximately 850,000 yen for NTSC TV to 8,000,000 yen for HDTV. The 8.6-inch "TV-on-the-wall" was displayed in an artistic frame and was described as suitable for museum-type applications. Its price was approximately 800,000 yen. (During the JTEC panel's trip the yen was exchanged at 128 to \$1.)

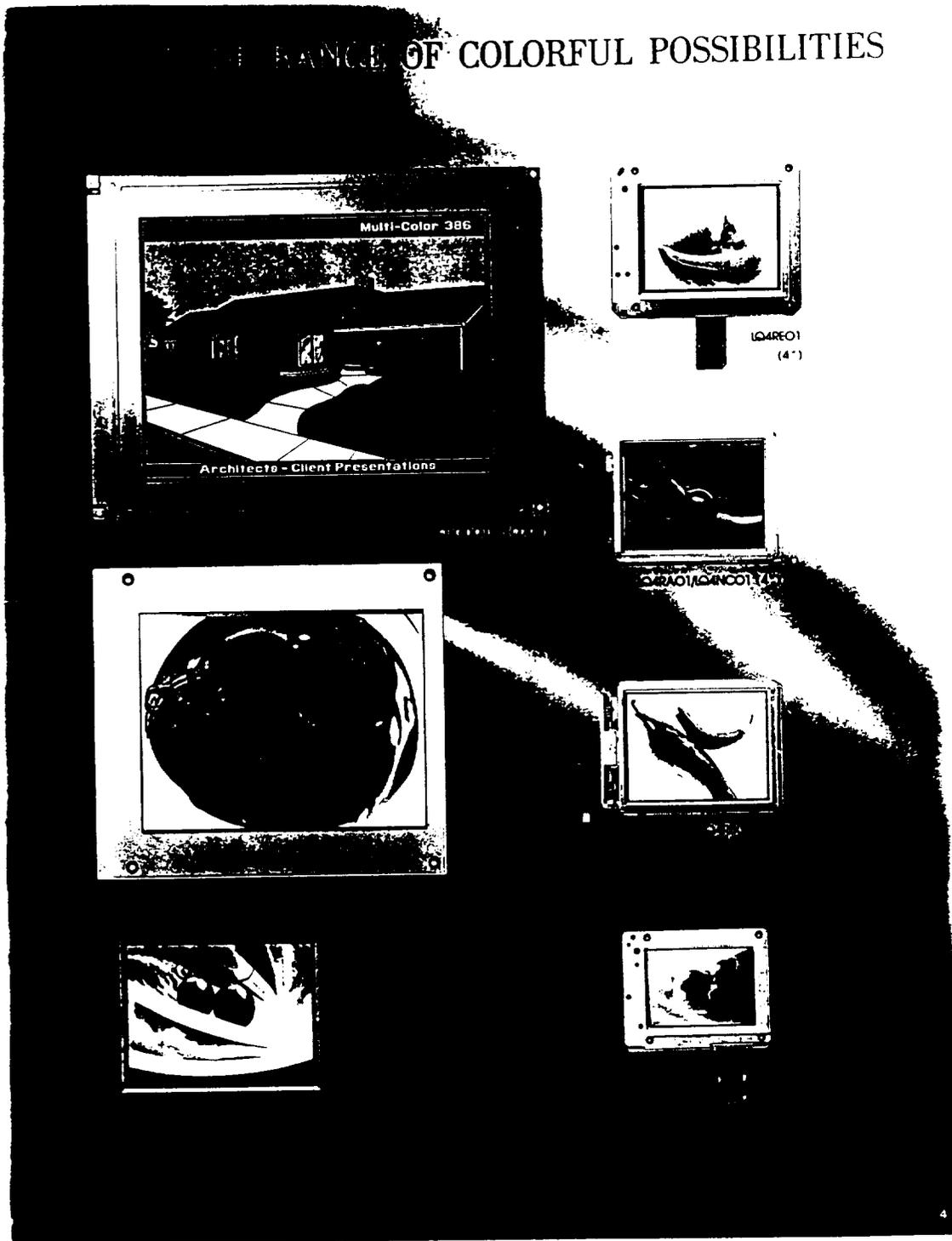


Figure Showroom.1.

CREATING A NEW WORLD OF LCD APPLICATIONS



Figure Showroom.2.



Figure Showroom.3.

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■ COMPLETE MODULE LINE-UP

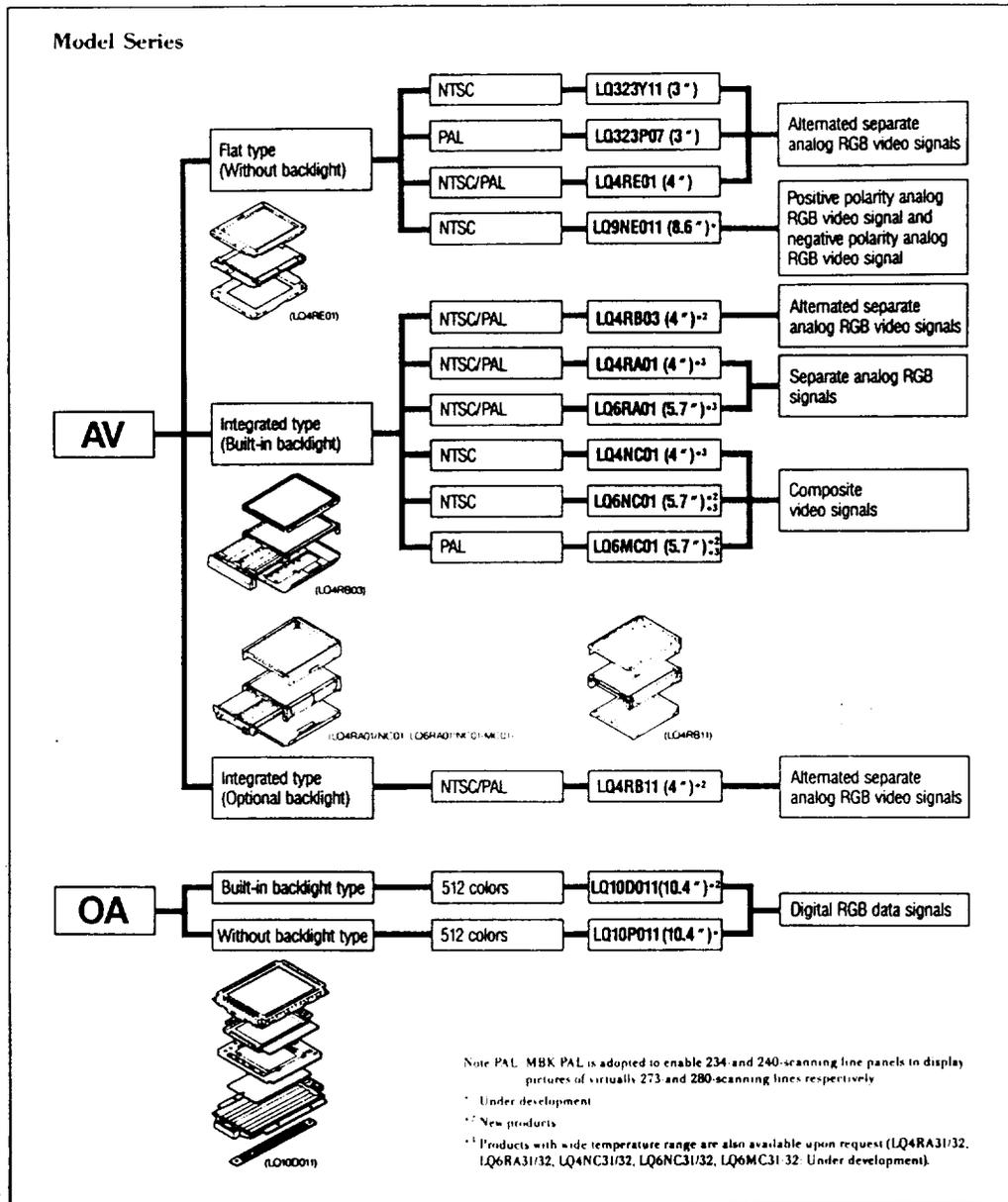


Figure Showroom.4.

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Site: **SONY**

Date Visited: October 4, 1991

Report Author: M. Thompson

ATTENDEES

JTEC:

Credelle
Thompson
Uyehara

HOST:

T. Yamada	Senior General Manager, R&D Corp. Planning
Usui	Chief Scientist
Urabe	LCD Division
A. Yasuda	Molecular Materials Research Dept.(Ferroelectric)
S. Umeya	Asst. Manager, R&D Planning
K. Watanabe	Manager, Project Promotion
I. Hiroyoshi	CCD/LCD

PRODUCTS

Sony entered the LCD field later than other companies and, therefore, has chosen a different strategy from the mainstream. It is focusing on small displays and poly-Si technology.

Sony started R&D on LCDs 20 years ago with TN direct drive segment type.

Their product history:

1. TN - 1978 Audio Peak Level Meter in Cassette Recorder. This had a high cost and was discontinued after two years.
2. In 1986 they produced a Laser Thermally Addressed Smectic LC light valve. The product is on the market and is high-cost and high-resolution (8,000 x 10,000).

3. Their most recent and current product (to be announced) is the color LCD viewfinder based on high-temperature poly-Si process. They believe a-Si TFT is best for large-size AMLCD, but they are focused on small-size poly-Si displays to overcome the interconnect problems with high-resolution a-Si. Also, they have had a 10-year history in poly-Si. They produce a super-thin-film transistor (see figure Sony.1).

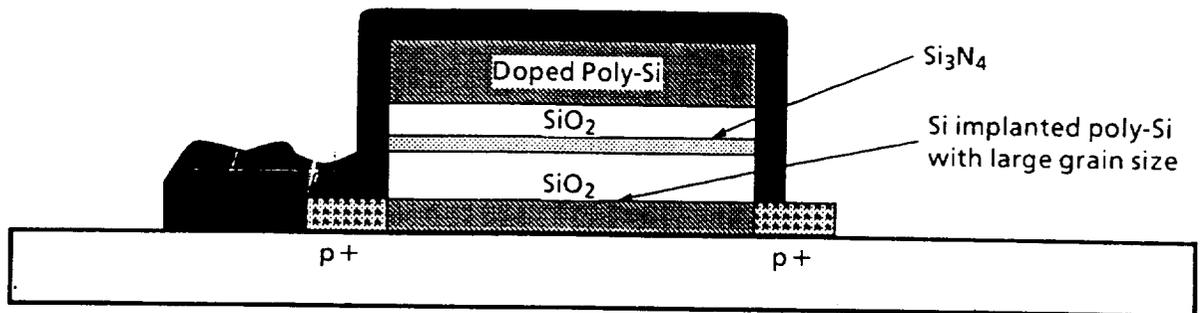


Figure Sony.1.

The multi-insulator structure is used to increase breakdown voltage. High-temperature processing is used to produce this device. CMOS circuits are used for the peripheral structure, and an LCD transistor structure is used for the pixel TFT to lower the leakage current. The implanted LDD regions are self-aligned. They use a three-phase switching gate to transfer RGB signals simultaneously. Therefore, the clock frequency is 1/3 and, thus, the power dissipation is reduced. However, signal delay is required, so a sample-and-hold has to be added.

They would like to make the viewfinder even smaller to enable more economic production on quartz wafers.

Device spec of "old" viewfinder:

0.7 inch diagonal, 77,600 pixels, 43% aperture ratio
 40 μm pixel, LCD is 5-6 μm spacing, 100 niEs, 2% transmission

We saw the "new" viewfinder design, which had higher resolution. They discussed the limits and issues of reducing the pixel size. Transistor size is $3 \times 5 \mu\text{m}$. Metal lines and spaces can be reduced, but fringing fields in the LC have to be reduced by shielding with black matrix.

At present, they are evaluating projector applications of their devices, but they believe such applications may not be cost-effective and, thus, larger area low-temperature poly-Si may be the best approach.

BASIC RESEARCH

They plan to use low-cost substrates for large-area poly-Si by using Excimer laser annealing. They need a glass substrate with $\Delta\alpha \sim 2-3 \times 10^{-6}/^\circ\text{C}$ and low compaction $< \mu\text{m}/100\text{m-hr}$.

The alternatives for low temperature poly-Si processes are:

1. LPCVD a-Si - Deposit 550°C , SPE annealing @ 600°C
2. LPCVD a-Si - 600°C
3. PECVD a-Si - ($<300^\circ\text{C}$)
4. Sputtered Si - ($T_d < 200^\circ\text{C}$)

Their choice is PECVD a-Si and laser annealing. With this approach, they have a-Si TFT in the matrix because of ease of obtaining low off currents and laser-annealed poly-Si for the drivers because of high on current. They laser scan the peripheral region only, resulting in a reasonable process throughput.

Deposition conditions for PECVD were:

Frequency: 50 kHz-13.56 MHz
Power: 0.05-1 W/cm²
Gas Pressure: 10 mtorr - 1 torr
Substrate temperature: 150-300°C

The optimum deposition temperature for a-Si is 250°C , whereas for optimum laser annealing to obtain good poly-Si, the deposition temperature is 150°C . The annealing source is 308 nm XeCl pulsed laser:

Pulse width: 20-50 ns
Pulse energy: 0.2-1.0 j/cm²
Repetition frequency: ~300 Hz

Laser annealing can also be used for doping activation. This processing technique has only local heating and is an ultrafast process (20 ns) with high throughput.

The beam size is 5 mm and, for uniform crystallization, 10 pulses per point are used. Beam pulse overlapping gives uniform crystallization.

SUBSTRATE

In a study of 7059 glass, Sony found that conventional heat treating at 600°C results in 15 μm compaction, whereas, after this laser treatment, only 3 μm of compaction occurs with further heat treatment at 600°C. They are concerned about the cost of 7059 glass and are considering using coated soda lime glass, in which case they must maintain the process temperature <350°C. They have measured the substrate temperature during laser annealing and found a maximum temperature of 150°C with a long decay time. They haven't measured the substrate with multiple pulses, but they claim that it is not a problem.

Sony obtains poly-Si grain size between 100 and 800Å for a 200Å-thick film, but they claim an even more important attribute in lattice matching between crystals, resulting in few defects.

$\mu = 50 \text{ cm}^2/\text{V}\cdot\text{s}$ (max value 150)
 V_{YH} = 3.5V, they claim very good stability
 I_{on} = 10-3A, I_{off} = 10-10A (a little high)

Laser-annealed impurity doping steps:

Recrystallization would probably be accomplished first, followed by the laser impurity doping steps.

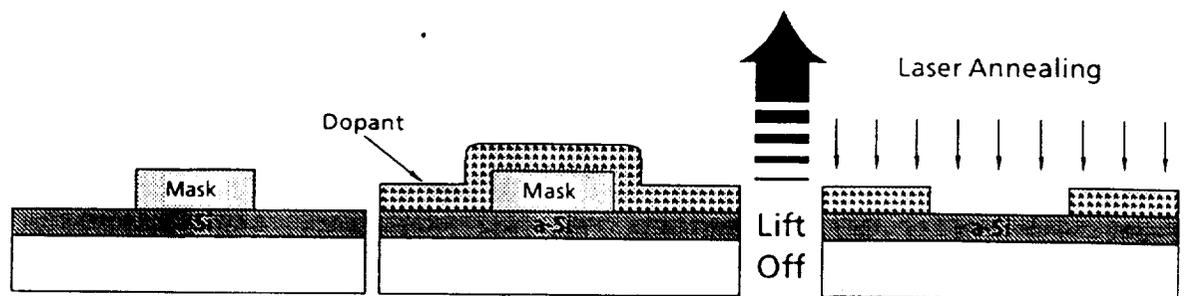


Figure Sony.2

They claim the great advantage of poly-Si is that a high aperture ratio can be achieved because the poly-Si transistor can be small compared with an a-Si TFT. They also claim the COG cost is half of the panel cost for a 1-inch product.

The main technology for the next few years, they think, will be a-Si followed by LT poly-Si. They will focus on low-temperature poly-Si for large areas and, in particular, work on Excimer beam shaping and homogenizing.

FERROELECTRIC LCD (YASUDA)

- Advantages-- 1000 x faster than TN
 Wide viewing angle
 Memory effect (greater than 1000-line display can be achieved)
- Issues-- Speed needs to be improved to obtain video rates, defect-free, molecular orientation.

Sony's approach is to use new materials to achieve faster response and wider temperature range. SiO oblique evaporation is used for the alignment layer, and a two-pulse drive method is used to address the cell.

Sony Fluorinated Compound vs. Conventional

Temp range	-30 to 75°C	vs.	-20 to 65°C
P-Si	33	vs.	<20
Response time	56 μ s	vs.	100 μ s

The response = 28 μ s delay + 28 μ s switching = 56 μ s. The conventional chevron structure has zigzag defects, whereas the bookshelf structure is more ideal. The oblique evaporation gives a 35° pre-tilt angle and a bookshelf structure which results in a contrast ratio >100. Sony's rub-free process also results in a reduction of ions.

The response time prediction is shown below:

<u>Year</u>	<u>Response time (μs)</u>
'91	56
'93	32
'98	<16

The bookshelf structure is better for shock resistance.

They believe the first application for FLC is office automation. Of the 5-10 companies working on FLC, Canon is the leader.

Their decision to make rather than buy LCDs is driven by several considerations:

1. Performance of LCDs has to meet Sony standard
2. Costs
3. For small-size LCD no one has achieved the required quality
4. Develop interdependent relationships with the suppliers

FLCs are a good candidate for large-size FPD. In the long term, 10 companies will survive in AMLCD--5 major companies and 5 second tier. Sony has a goal of first being number one in manufacturing small-size poly-Si displays, and then it will increase the size.

Site: **STANLEY ELECTRIC CO.**
Yokohama

Date Visited: October 4, 1991

Report Author: T. Credelle

ATTENDEES

JTEC:

Credelle
Thompson
Uyehara

HOST:

H. Horiuchi
M. Aizawa
Y. Naito

Stanley is basically a lighting company, founded in 1920 to develop automotive lighting. Besides normal incandescent lamps, they produce bright LEDs and are investigating discharge lamps. At their Tsukuba Research Center, they are looking at biotechnology. Today the main products are automotive lighting, displays, control panels, and biotechnology for light conversion. LCD sales are approximately ¥10 billion; total company sales are ¥200 billion.

CSH-LCD

LCD research began in the early 1970s; in 1984-85 Stanley began production of dashboard panels using direct-drive LCDs (guest host at first, then TN). They investigated STN but became intrigued by the homeotropic aligned nematic approach being developed by LETI in France. To develop the technology they applied for and received funding from Japan Research Development Corp. (JRDC), which lends interest-free money to companies for research. If the development is successful, then the money is repaid. JRDC has funded ¥2.3 billion in R&D, and Stanley has produced very nice-looking CSH-LCD (color super homeotropic LCD) in sizes up to 10 inches. The 10-inch panel was 640 x 480 pixels, 50 nits brightness, 15:1 contrast ratio, and 15 W power. Viewing angle is improved over STN, and gray scale performance is superior to STN. CSH advantages, according to Stanley are (a) easier gap control, (b) wider viewing angle, even in gray scale, and (c)

potentially faster response time. The response time achieved to date is 250 ms (average of rise and fall); this is now inferior to color STN because of recent improvements. Main challenges for the technology are materials availability (LC manufacturers are focusing on TN and STN materials) and wide temperature range (especially for automotive). Today the resolution limits are determined by the multiplexing ratio (240:1 max). Stanley hopes to develop higher resolution if the basic VGA size is successful. Another serious limitation for portable PC use is transmission efficiency; the CSH transmission is 1.5-2.0%, about half that of color STN.

Part of the arrangement for the funding from JRDC is that a pilot production be established. Stanley is planning to do this but did not state the size of the line or the timing.

FERROELECTRIC LCDS

Stanley is doing only R&D in this field and did not discuss it.

TFT LCDs

Stanley has built a-Si TFT LCDs for potential use in automotive applications. All the major avionics manufacturers have approached Stanley, and they are working on some programs (confidential). They have demonstrated a 6-inch color TFT LCD in the past, but did not show it this year at the JES. They said that the requirements for automotive applications are very difficult; the biggest challenge is cost.

BACKLIGHTS

Stanley has developed RGB cold-cathode fluorescent lamps for LCD backlights. They are used by Stanley and others; outside sales are larger than inside sales. They now have 3.0-mm-diameter bulbs in production; Stanley feels that this is the minimum size practical for the near future.

EL backlights have also been developed for mono STN. Brightness is a problem, but 400 nits is perhaps achievable (STN transmission is typically 15%, so 400 nits translates to 60 nits). Efficiency of 4-5 lm/w is possible in either white or green. Biggest problem now is life; reports of 5000 hours at lower brightness (200 nits) have been made.

THIN-FILM EL

Stanley is researching thin-film EL and is focusing on organic materials at their Tsukuba Research Center. They have produced blue EL that "is visible in the lab" but said that life is a problem.

PROJECTION SYSTEMS

Stanley has produced metal halide lamps for automotive applications, but has not yet started working on projection lamps; it is not their main business. They indicated that they have some R&D in projection systems, but the level of effort was not stated.

Site: **TOKYO UNIVERSITY OF AGRICULTURE & TECHNOLOGY**
(Dr. S. Kobayashi)

Date Visited: October 4, 1991

Report Author: W. Doane

ATTENDEES

JTEC:

Doane
Larimer
Slusarczuk
Tannas

HOST:

Dr. Shunsuke Kobayashi

We met with Dr. Kobayashi and two students. He showed a video of Tokyo University, then gave an overview of his current research.

NOTES ON CURRENT RESEARCH OVERVIEW

Upon going over items on the handout list "Research Themes of Kobayashi Laboratory" (following), we asked the following questions (Q) and received the following answers (A):

- Q: On your surface studies, what alignment materials are being studied?
A: Alkyl branched polyimides, Langmuir-Blodgett (LB) films, and polypyranol conductive polymers.
- Q: Why conductive polymers?
A: These materials are needed to eliminate "2nd order" cross-talk (ghosting from surface charge build-up).
- Q: Why LB films?
A: Need a way to avoid rubbing of AMLCD substrates. The films are put on by dipping.

Q: What are the LB films materials?

A: Polyamides (derivatives thereof).

Q: What are the weak points of ferroelectric displays and materials?

A: Surface stabilization problems are being solved, he believes--gray scale worst problem.

Q: How can gray scale be solved?

A: Here he refers to one of his papers, Kimura et. al., *SID Proceedings*, 31, 139-143 (1990), in which he explains how LB films can be used for surface treatment to yield gray scale dependent upon applied voltage.

FUNDING OF UNIVERSITY RESEARCH

In response to a question, Professor Kobayashi gave the following list of funding sources for Japanese university research:

1. Operating funds evenly distributed among faculty (¥3 million).
2. Ministry of Education, Science & Culture - Like the U.S. National Science Foundation (NSF), this agency supports basic and applied university research. About 30% of Japanese faculty are supported. There are many programs; e.g., \$5 million/50 professors for center-type activity (well-focused research).
3. Donations.
4. Contract research with industry.
5. Cooperative research with industry. Here Prof. Kobayashi has a program with some 5-6 display companies on FLCs, AMLCDs, HD LCDs, LC alignment layers, flexible displays. Gave us some literature on this ("Cooperative Research Center," attached).

Overhead costs are handled differently than in the United States. In Japan, faculty are directly charged for electricity, water, and so forth.

R & D SUPPORTING AGENCIES IN JAPAN

Ministry of Education, Science & Culture (MOE or "Mombusho") - Has many agencies, including the Japan Society for the Promotion of Science (JSPS). JSPS includes foreign exchange of students. Each agency has many committees covering such areas as laser technology and material science; each has representation from both government and industry.

Ministry of Posts and Telecommunications (MPT) - This has projects such as The High Definition Television Engineering Corporation (HDTEC), a joint government-industry funded venture.

Ministry of International Trade and Industry (MITI) - Also has many projects and committees supported in part by government and in part by industry, e.g., Giant Technology Corporation (GTC) for 40" direct view display development. Another example: Japanese Association for Technology Transfer (JATT) which has 80 committees, one of which (GTC) Professor Kobayashi chairs on displays. This committee has 80 companies, one being Dainippon Ink.

Bench Technology Foundation or Japan Critical Technology Company: (\$100 million) received funding from sources such as NTT, and supports GTC. Other private companies also support GTC. GTC and HDTEC are small compared to the U.S. agency DARPA.

MAJOR ISSUES THAT CHARACTERIZE DISPLAYS

Professor Kobayashi gave the following outline of issues important in a display:

1. Information content
 2. Viewability
 - a. Legibility (contrast ratio and luminances)
 - b. Full-color capability
 - c. Gray scale
 - d. View angle
 3. Cost of driving circuits
 4. Production costs (yield, throughput)
 5. Space (flat panel, weight)

(Often trade-offs between 1 & 2; 1, 2, & 3, 4)
- o No technology can cover all of these well.
 - o Kobayashi claims that all LC technologies can cover these sufficiently and that all, if pursued strongly enough, could be marketable technologies.
 - o All AM companies make an active matrix display a different way, but all are very enthusiastic and will succeed because of fierce competition.
 - o All LCD technologies should be explored.
 - o Need for direct-view display w/o backlighting.

Tokyo University^{*}
of
Agriculture and Technology
Faculty of Technology, Graduate School of Technology

Department of Electronic Engineering
Division of Electronic and Information Engineering

*** Electronics**
Motto...3E * Exotic Materials
*** Ergonomics of LCDs**

1991 Research Themes
of
Kobayashi Laboratory

:Surface anchoring of LCs	D.-S. Seo (PhD)
.Theory	H. Matsuda(M)
.Polar anchoring	T. Isogami
.Torsional anchoring	K. Muroi
.Conductive orientation films	
:Legibility of LCDs	A. Mochizuki (PhD)
.STN, Ch-N, FLC	
:Active matrix (TFTs)	Y. Toko (R)
:Langmuir-Blodgett Films	H. G. Suen (R)
.LC alignment	A. Ishizaki (M)
.MIM-diodes	H. Abe
:Ferroelectric LCs	M. Kimura (M)
.Bistability	M. Ito
.Gray scale	
:Optical neurocomputer with FLC	C.M. Gomes (PhD)
.Dynamic weight matrix	H. Sekine (M)
"Dywmmax Optical Neuro Computer"	T. Yamazaki (M)
.a-Si photoconductor	Y.G. Jin (M)
	A. Nakagawa
:Electroclinic effect	Y.B. Yang (PhD)
.SmA-SmC* phase transition	T. Bang
:Optical integrated circuit	B.X. Chen (PhD)
.Utilization of EC effect	
.Nonlinear optics	
.Optical logic	

^{*} Retyped from handout provided by Professor S. Kobayashi.

Cooperative Research Center⁺

1. Aim of the center

The Ministry of Education (MOE) established a new system called "Cooperative research with Incorporated Organization" by laying down a law issued on May 11th, 1978. The aim of this system is to promote cooperative researches which will be done by the joint teams considering of the university members and those from the incorporated organizations (mostly private companies).

2. System of cooperative research

The system of the cooperative research is generally flexible compared to other existing systems in the patent ownership, budgetting, and so forth.

The system is characterized by the classification of the budgeting category A, B, and C as shown on Table 1.

Table 1. Classification of Research Projects

Category	Budget Supplied from IO (1)	Budget supported by MOE (2)	Research Fellow(s) from IO (3)
A	yes	yes	yes
B	yes	no	yes
C	0	no	yes

legends: (1) Incorporated Organization
 (2) The Ministry of Education
 (3) The annual fee for a fellow is ¥412,000.

To provide the laboratories and facilities for the project teams the MOE constructed 10 buildings of the cooperative research center already in each of 10 national universities as of 1990. The exact name of the center differs from one university to the other according to the locality and social environment.

⁺ Retyped from an original document supplied by Professor S. Kobayashi.

3. The Cooperative Research Center in TU of A/T

Regarding the layout and facility of the center, it is a three story building locating in the south-east corner of the Koganei campus having a branch room in the Fuchu campus. The integrated area of the main building is 1300 m² consisting of 26 laboratory units (23 m² each), a clean room facility (10,000, 1,000, 100 grade), that for biotechnology of P-2 grade, a green house, an EM shield room, offices for the administration and director, a seminar room, and others.

In our university, the building of the CRC was completed on March 31st, 1990.

In the fiscal year of 1990, 23 research projects were conducted using the laboratories and facilities of the CRC. In 1991, 30 projects have been conducted.

Reflecting the nature of the university, the research projects can be divided into the following four fields; new materials and electronic or optoelectric devices (40%); biotechnology (40%); energy (10%); and mechatronics (10%).

4. The process for accepting and conducting the research projects

The process adopted by us ranging from calling for projects to the start of them is as follows:

- a. The MOE issues the call for projects (CFP) to all the national universities,
- b. the president of the university send this CFP to the dean of faculties (the process here after may differ as the difference of the universities),
- c. each faculty makes an announcement of the CFP to all the faculty members with application formats (the deadline for the submission is 31st January).
- d. the faculty member who is interested in conducting a cooperative research with a incorporated organization (mostly a private company) makes a contact and negotiates with a his/her counterpart to decide title of the project, category of the research (see Table 1), amount of the research budget, and name(s) of the research fellow(s),
- e. approval for accepting the applied projects is done officially by the faculty member meeting,
- f. approved projects is transferred to the board of trustee, after getting approval by this organization, a decision making by the university is done.

- g. all the projects are again sent to the MOE to have a national budgeting process,
- h. the projects decided to be conducted in the center are transferred to the steering committee of the center headed by the director. A representative of each project (a faculty member) is free to use the center facility or not according to his/her choice.
- i. The steering committee make a decision who will use which lab and facility, then the projects start.

5. Inviting Professors

The center has three chairs for inviting professors for a fiscal year: six inviting professors will be also invited by diving the period of a fiscal year.

6. Publications and open seminars

The center publishes several kinds of archives such as a brochure, news letters (3 times in a year), and the annual report.

Open seminars are held in the campus almost every two months on the topics of the projects and those of relevant to them. Announcements are made by direct mail to the standing members accounting 400.

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14. Japan Display '92. "Call for Papers."

Site: **TOPPAN PRINTING**
Tokyo

Date Visited: October 9, 1991

Report Author: M. Thompson

ATTENDEES

JTEC:

Doane
Thompson
Uyehara

HOST:

K. Shioya	Chief Manager, Sales Promotion Department (Interface)
K. Shinki	General Manager, Overseas Sales Div.
Y. Tanosaki	Chief Manager, R&D Administration
M. Tani	Assistant Chief Researcher
J. Sasaki	Sales Promotion Dept.

Toppan is an independent company with a 1991 revenue of \$54 million working in publishing, packaging, photo fabrication, and electronic precision components. They have sophisticated CAD/CAM and produce photomasks, PWB, lead frames, shadow masks, color filters for LCD, and image sensors. For example, they have produced X-ray masks, 62-layer PWB, 336-pin lead frames, and TAB tapes.

Toppan is the world's largest producer of color filters for CCD, LCD, and image sensors. At the Shiga Plant, dyed gelatin and pigment dispersed filters are produced, defined with an accuracy of $\pm 5 \mu\text{m}$.

Dyeing is the most popular method, with gelatin as the binder. However, this method has some problems. Gelatin is not strong enough, and colors fade because the heat resistance (180°C) and high-light resistance are insufficient. Acrylic binders have superior heat resistance (260°C) and better high-light resistance. Dye filters produce better selectivity than pigment-dispersed filters. Toppan also produces multilayer thin-film dichroic filters, but they are expensive.

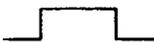
There are four principal methods for producing filters: dyeing pigment colorant, printing, electric deposit, and dichroic. For LCDs the dye-based gelatin has been

the predominant method, but the pigment-dispersed filters are expanding because, compared with the gelatin filters, pigment-dispersed filters prove to be superior in light resistance for OA, TV, automobile and aircraft applications.

The production cost is similarly high for dye and pigment filters. The pigment-based filter is spun onto the substrate. For the pigment-based filter, the material cost is higher than for the dye filter, but the production method is easier. There is only one supplier, Fuji-Hunt, for pigment-based filter material, which requires other vendors to reduce material cost. Roller coating, when perfected, could reduce the amount of pigment filter material dramatically. A proximity aligner is used to pattern the filters. Low-reflectivity chrome is used for the black matrix and is patterned with a stepper. An overcoat is deposited on the gelatin filters (but sometimes not for pigment filters) before the ITO is deposited. Improvement in the transmission of pigment-dispersed filters is under investigation but no dramatic improvement is expected in the short term. If the pigment is made smaller, the transmission increases, but generally speaking the light resistance has the tendency to gradually decrease.

Electro depositing production of color filters can only be used with certain filter layouts (like stripe) that have a continuous path from one side of the display to the other. Printing technologies offer the possibility of fabricating low-cost filters. The main issue with printing is the topographic profile of the filter and the maximum size of the substrate. A comparison of the dye, printing, and pigment methods is shown below.

Table Toppan.1

	<u>Dyeing CF</u>	<u>Printing</u>	<u>Pigment</u>
Pattern			
Process	Long	Short	Medium
Cost (main factor is yield)	100	80	100
Working display	Present 14" Max 20"	Present 4" Max 10"	Present Max 20"
Glass size	400 mm	300 mm	400 mm

In summary, the main emphasis is on reducing cost of filters.

Site: **TOSHIBA ENGINEERING LABORATORY**
Date Visited: October 3, 1991
Report Author: L.E. Tannas, Jr.

ATTENDEES**JTEC:**

Covert
Credelle
Hoffman
Tannas

HOSTS:

Hiroo Hori	Chief Specialist
Yasuhisa Oana	Senior Manager
Makoto Ikegaki	General Manager

The Toshiba R&D visit was held at the Electron Device Engineering Laboratory in Yokohama, where we discussed the issues of a-Si TFT LC and related displays. At the conclusion of the meeting, the committee visited Toshiba's exhibit room and saw operating examples of the 10.4-inch (640 x 480), 13.8-inch (1052 x 900), D-size (1024 x 1024) and 3ATI-size avionics displays, all in color using a-Si TFT LCDs.

The discussions were open and free-flowing, and the following key points were made:

- o The Engineering Laboratory supports all other divisions in the Toshiba ET&D Group, with over 90% of the activities on LCDs.
- o The CRT group does its own research.
- o The remaining 10% of the activities in the laboratory are advanced image sensors and printer heads.
- o This Engineering Laboratory supports the DTI (Joint IBM/Toshiba venture) and Toshiba LCD factory in Himeji in basic device and process information and in basic materials development.

- o The Engineering Laboratory does work relating to a three-year time frame, and the R&D Laboratory in Kawasaki does work relating to a five-year time frame.

The goals of the Engineering Laboratory are focused on several products and on high yield and productivity:

- o a-Si TFT LCDs 10.4" VGA color
- o Higher information content displays:
12" to 14" to 16" (1024 x 768 and 1024 x 1280)
- o Advanced instrument displays for avionics
ARINC D (1024 x 1024) and 13.8" (1150 x 900) Sparc, Electronics Laboratory
- o Simple matrix LCDs:
High contrast, flicker-free, quicker response, brighter, gray scale, cross-talk free, higher multiplexing
- o Ferroelectric LCDs
- o Polymer-dispersed LCDs
- o Poly-Si TFTs
- o LCD for video projectors
- o Advanced image sensors and printer heads

Staffing of people involved in LCD research:

- o 40-50 in Kawasaki
- o 100 in Yokohama
- o 200 in Toshiba Himeji
- o 50 in DTI Himeji

Sales in LCD Division:

- o 1990, \$200M
- o 1991, \$300M
- o STN will grow 10-15% per year
- o TFT a new market
- o STN and TFT by 1995, one trillion yen (moderate prediction 500-600 billion yen), 70% STN, 30% TFT.

With more than 80% of the avionics cockpit CRT display market, Toshiba feels it must continue its participation in the avionics market.

Toshiba is studying all forms of LCDs--ECB, PDLC, MIMs, FLCDD, poly-Si TFTs, Philips diode approach--and have decided to concentrate on STN and TFT approaches. They are using a-Si TFTs but are continuing to study poly-Si. Even for HDTV projectors, poly-Si may cost more than a-Si TFTs in 3" and 4", but Toshiba will

study more. Toshiba is studying low-temperature, laser-annealing, thermal-annealing, and ion-doping aspects of poly-Si TFT LCDs.

The Toshiba representative made several important observations relative to the future of LCDs:

- o Toshiba does not have a strong interest in ECB or ferroelectric LCDs in the future.
- o The STN LCD must be black and white or color because of future demand.
- o Compensated STN and a-Si TFT LCDs will coexist for a long time and may never cross over in market share.
- o Color STN still has yield and speed problems due to color thickness uniformity and cell thickness limitations.
- o Toshiba buys pigment-type color filters from outside but continues to study different methods. Strong interest in printing method.
- o Toshiba is making its own LSI drivers with up to 240 outputs mounted on "slim-tab," and will sell to anyone.
- o Toshiba thinks that HDTV will be done with LCD projectors.
- o There is a renewed interest in direct-view color plasma panels for large displays and HDTV. However, there are developmental issues such as poor brightness, efficiency, color gamut, drivers, and life.
- o GTC's funding has been reduced from ¥10 billion to ¥2 billion and so it is working on manufacturing technologies for the one-meter LCD panel rather than making a one-meter panel. Hitachi, NEC, and Sharp may make a panel later.
- o Toshiba sees 15 inches or 16 inches as the size limit for LCDs using today's production methods. Anything larger will need a completely new production technology. Toshiba does not see the adoption of 500 mm substrates before the year 2000. SEMI has a standard for substrates of 300-500 mm on a side of 50-mm steps. Toshiba is presently standardized at 300 mm x 320 mm.
- o The crossover display size between CRT direct view and projection is between 36 and 40 inches.

- o The "TV on-the-wall" for consumers is too expensive now and for the foreseeable future.
- o 8.5 inches is too small for VGA; therefore, 300 μm pixel pitch is appropriate for direct view. 150 μm pixel pitch is too small and is not needed for direct-view displays.
- o The FPD market will not be saturated in the next ten years.
- o Toshiba will not be doing any more plasma or EL research. NEC has stopped its plasma work.
- o Toshiba Computer Division may have adopted plasma because of its fast response time. Monochrome plasma displays are quite competitive with STN LCDs for notebook computers.

The next phase will be in improvements in production processes and machinery.

- o High throughput is the highest priority.
- o PECVD needs improvement.
- o Cleanliness improvements are needed to improve yield.
- o Alignment layer still needs a lot of improvement. Presently, Toshiba uses a polyimide rubbing technique.
- o Glass shrinkage is a big problem due to 350°C processing temperature; five ppm is too much.
- o More automatic test equipment is needed and expected from the United States in the next two to three years.
- o Mobility is at 1.26 and is OK.
- o Design rule used is six μm average, three μm for TFT, eight μm for color filters and edge connections. Nikon Stepper can do one or two μm . Canon Mirror can do 3 or 4 μm .
- o Next generation design in 2-3 years will be designed for a yield of over 80%.
- o Toshiba trying to stay completely away from repair. They do not repair array with lasers. Only repair being used is in TAB bonding.

The tour of the Toshiba display room demonstrators gave a clear and lasting impression of the accomplishments of Toshiba engineering and manufacturing.

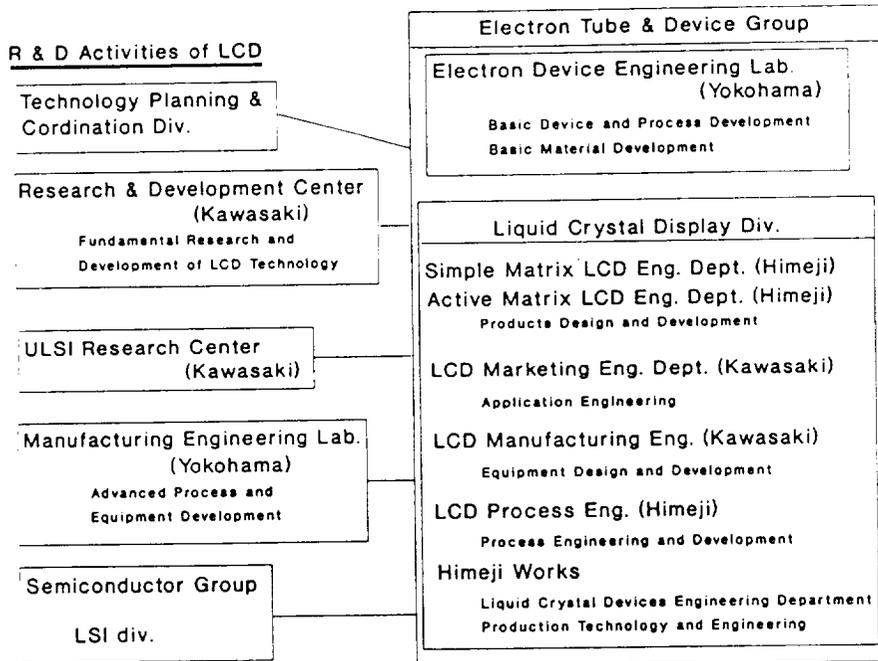


Figure Toshiba.1. R & D Activities of LCD

Field of Activities

- o Advanced Device Development
- o Driving Circuit Technology and LSI Development
- o Advanced Process Development
Thin Film Deposition
Sophisticated Lithography
LCD Cell Process
- o Liquid Crystal Material
Color Filter
Back Light
- o Total Simulation

Figure Toshiba.2. Electron Device Engineering Laboratory

Site: **TOSHIBA & DTI**
Date Visited: October 3, 1991
Report Author: W. Doane

ATTENDEES

JTEC:

Doane
Hoffman
Firester
Thompson

HOST:

S. Arai	Senior Manager, LCD Marketing and Engineering Department
K. Kawasaki	Manager, Simple Matrix LCD
T. Sumita	Executive Director, DTI
M. Ikegaki	General Manager, Electronic Development and Engineering Lab, Toshiba

Himeji works employs 5,000 people and has the following production volumes:

CRT:	450,000 per year
Transistors:	412 million per month
Diodes:	325 million per month
SAW devices:	6 million per month
Fluorescent tubes:	6 million per month
LCD:	250,000 - 260,000 per month

Between 50% and 60% of Toshiba LCDs are used internally on Toshiba products. They supply displays for NEC and IBM products as well as their own.

TOSHIBA STN

They focus on large-size STN products with resolution of 640 x 200 and 640 x 480. They have developed their own drivers and controllers and developed the TAB bonding in their own Engineering Manufacturing Department. They produce two VGA displays on a 300 x 360-mm substrate.

The process sequence is as follows:

- 1) Starting material, ITO-coated glass, is purchased
- 2) Clean -- ultrasonic, detergent and water cleaning
- 3) Resist coat -- they use Nakan roller coater with moving drip feed for better uniformity
- 4) Dry
- 5) Expose -- proximity aligner
- 6) Etch
- 7) Clean
- 8) Polyimide coat -- Shibairi Coater
- 9) Bake
- 10) Rub -- Toshiba machine, developed internally
- 11) Print seal -- screen printing
- 12) Apply spacers -- spacers are sprayed on one plate of the cell using a proprietary machine developed internally. Spacers are 6-7 μm with a 0.03- μm tolerance. The spacer population is monitored after spraying.
- 13) Curing to obtain better gap uniformity
- 14) Assembly
- 15) Filling -- liquid crystal is filled on many cells clamped together and dipped in the liquid crystal in a vacuum system.

Cassettes contain 25 substrates.

This entire operation was contained on the third floor of their LCD building. There is a TFT line on the floor below. The LCD line is operated three shifts a day, and there is a facility clean-up after each shift. 50,000 LCDs are produced per month per line, and there are two lines. A third line was to be added in April 1992.

Having toured the sample matrix LCD line, we went to the DTI facility, which is on the same site but is separated from the Toshiba facility by a security fence.

DTI -- AMLCD

DTI was established on November 6, 1989, as a joint venture between Toshiba and IBM Japan. It occupies 27,600 sq. meters of land and has 28,300 sq. meters of building floor space, with an investment of ¥30 billion. As of 10/1/91, it had 377 employees, about one-third of whom were on assignment from Toshiba and IBM Japan; the other two-thirds were new employees who had received six months' training at the Toshiba TFT facility.

There are ten members of the board, five each from Toshiba and IBM Japan. The management structure is shown in figure DTI.1.

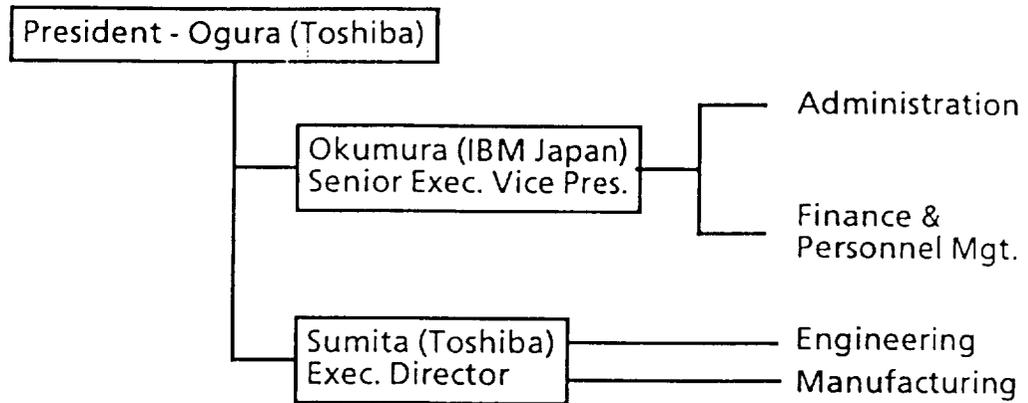


Figure DTI.1.

DTI is a manufacturing company only and has no marketing; 50% of the products are delivered to Toshiba, and 50% to IBM Japan.

DTI will produce large-size ($\geq 10''$) AMLCDs for office automation applications. Toshiba has its own line, which is supplying other applications and produces mostly smaller sizes. The layout of the site is shown schematically in figure DTI.2.

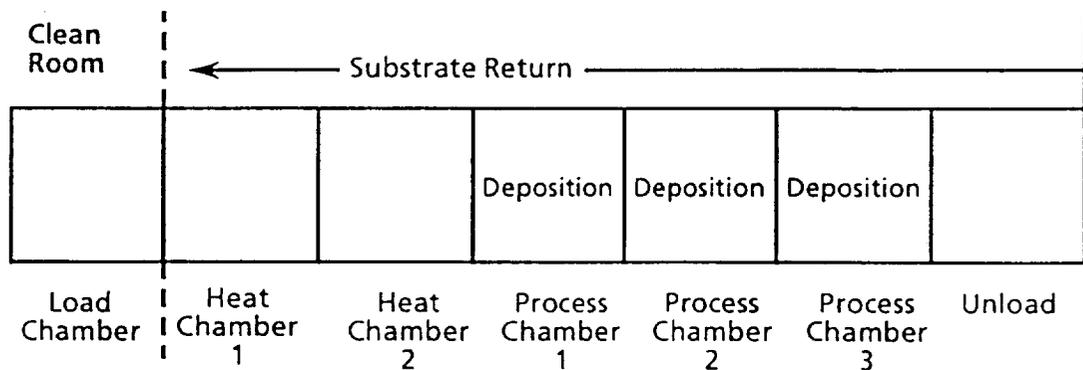


Figure DTI.2.

Substrates were 300 x 400 mm Corning 7059, stacked in cassettes of 25 plate capacity.

Third Floor

Six Tokuda CDE 702 dry etchers were used for gate metal. Four plasma etchers were used for SiN etch. Two Canon MPA 2000s were used for alignment, and the resist was spray-developed. Canon was apparently preferred over Nikon for cost and throughput reasons.

There were many PECVD machines. The one we could see was a seven-chamber system, the recent Anelva model. A schematic of what was deduced is shown in figure DTI.3.

A window frame holder for four substrates was used in PECVD, with manual loading at the time of our visit. Presumably, this was a double-sided deposition machine, which means that eight substrates were processed in each chamber. Automatic loading was being evaluated on one of the PECVD machines.

Manual transportation of cassettes was used, with automatic loading from transportation cassettes to machine cassettes.

Second Floor

Half of this floor was used to finish the TFT process and contained Kashiya dry etchers, RIE etchers for MoAl, and two more Canon aligners. The pad metal was sputtered MoAlMo.

The rest of this floor was used for the liquid crystal process. We saw seven glass cutters, four filling machines, and a Nikon particle-inspection machine. ITO and signal line are wet-etched.

First Floor

This was a class 1000 room used for TAB assembling to LCD.

No TFT repair is used because of the high labor content: 70 people operate each shift in the facility. For three shifts, 120 people are used on array production, 40 on cell production, and 50 on module assembly. When the process is mature, the number of operators should be reduced by one half. The cycle time for production is as follows: 3 weeks TFT, 1 week cell, and 1 week module assembly and test.

The transportation of cassettes is done without boxes, but they are considering using closed boxes in the future.

Our DTI hosts said the hardest part of the process is dust control in photolith and CVD. They believe control of the electrostatic charging problem is the equipment

vendor's responsibility. The major materials costs are color filters (which they buy), substrates, and drivers.

The AMLCD capacity in this facility will be 1 million per year by 1995. This was an outstanding visit, and our hosts were very open and informative.

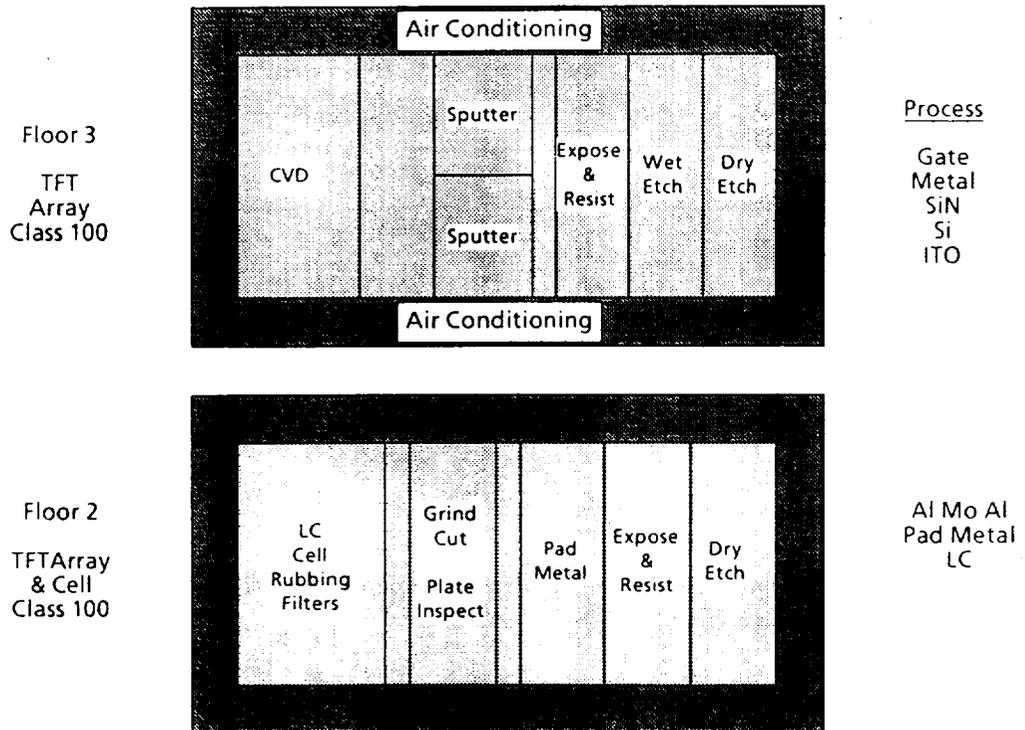
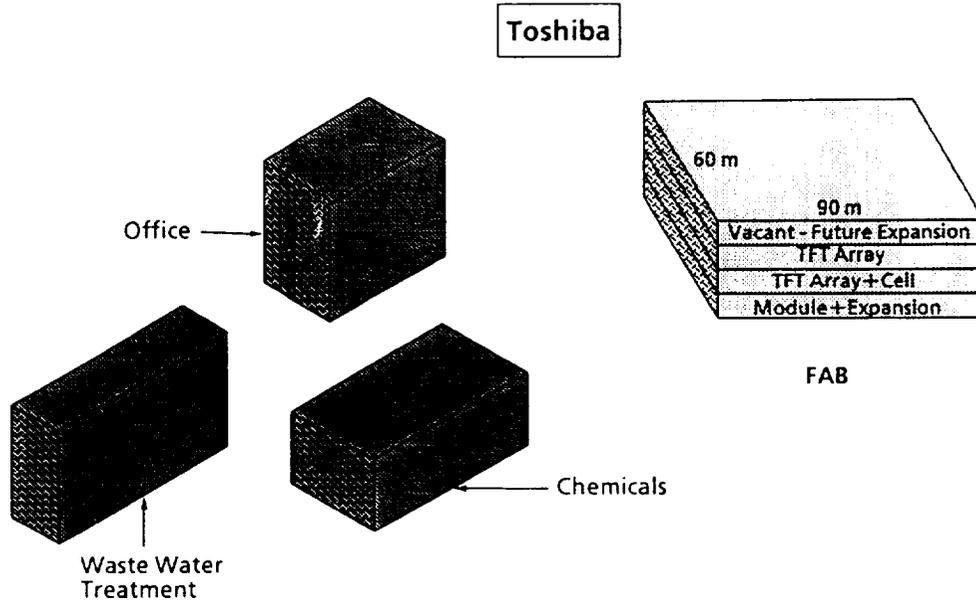


Figure DTI.3.

Site: **TOTTORI UNIVERSITY**
Date Visited: October 7, 1991
Report Author: M. Slusarczuk

ATTENDEES

JTEC:

Slusarczuk

HOST:

Hiroshi Kobayashi
Shosaku Tanaka

Tottori University performs research on electroluminescent materials. Their focus is on improving the performance of color and white phosphors. Their laboratory, which is about 600 ft², contains the following deposition equipment:

Sputtering - hot wall epitaxy - electron beam evaporation.

The general thrust of their research is using potassium, sodium, or lithium as the charge-compensating material. The following single-color phosphor combinations are presently under study;

Red- CaS: Eu
Green - ZnS : Tb, F
Blue (485 nm) - SrS : Ce, K

The white phosphor combinations are

SrS: Ce, K, Eu
SrS: Pr, K (appeared to have a disproportionate green component)

They have shown reasonable progress in both blue and white phosphors, especially using an Ar-S atmosphere anneal at 630°C. They have shown three colors using the white phosphor with both dye and interference filters. The dye filters provided better viewing angle. Brightness achieved has been 50 nits at 60 Hz and 900 nits at 1000 Hz. The efficiency is about 0.4 l/W.

We were also shown a laser laboratory that had a dye laser with femto second optics for measuring nonlinear optic properties.

Answers to direct questions: In order for EL technology to be viable, a 5- to 6-factor improvement in blue brightness is necessary.

They felt that RGB and white with color filters each offer different trade-offs. They believed that EL could support 1000 x 1000 pixels without serious cross-talk problems. Gray scale and cross-talk minimization are both areas that require additional work.

DC EL powder/thin-film hybrid is being studied by Nippon Sheet Glass, which has shown a 640 x 480 display with 16 levels of gray with pulse-width modulation.

ITO resistivity is not something that Tottori's researchers have given much thought to.

Tottori University works with a number of industries: Sharp, NEC Kansai, Oki, Fuji Electric, Nippon Sheet Glass, Matsushita, Komatsu, and Tosco--all companies with some level of EL research.

The University chooses to publish its results rather than to patent the discoveries. Part of the motive is to further the status of EL relative to other display technologies.

MEETING WITH PROFESSOR MUNEO OKA, DEAN OF ENGINEERING

We had a discussion with Professor Muneo Oka on the sources of funding for universities and the nature of the industry-university interaction. Each research group gets ¥3.5 million from the Ministry of Education. This money covers one professor, one assistant professor, and one lecturer. If the group is part of a PhD-granting department, then the amount increases to ¥6.5 million. Tottori University has no PhD program in engineering yet but is in the process of trying to establish one. These funds constitute the "even distribution" money.

If a particular professor has been performing excellent work and the Ministry of Education feels that this work is in an important area, then it awards a larger sum--on the order of ¥100 million. This money covers the work of multiple professors, about 10, from across several research groups. Half of the money goes for equipment, the rest for operational costs, excluding salaries. The projects are usually for three years. They are not renewable.

Selection of the larger projects is done through consensus, which "bubbles up" through meetings at societies, universities, etc. Final selections are made by a committee of about 10 senior professors from around the country (though in reality they are mostly from the Tokyo area.) There is currently an initiative to start

including smaller universities in the process. Until recently, most such grants went to the major universities only.

Graduate students are supported by a "stipend" at a rate of about ¥5,000 per day for up to 30 days.

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Site: **TOHOKU UNIVERSITY**

Date Visited: October 2, 1991

Report Author: W.E. Glenn

ATTENDEES

JTEC:

Glenn
Credelle
Doane
Hoffman
Larimer
Thompson

HOST:

Dr. Tatsuo Uchida Professor, Department of Electronics Engineering,
Faculty of Engineering, Tohoku University

Dr. Uchida's research at Tohoku University is primarily in the area of liquid crystals. He is very active in the SID. He recently held a conference on LCD technology with an attendance of about 500 people. He reported that in universities, 100-250 people are working in the field of liquid crystal research. Most of these people are chemists or physicists. His laboratory has about 15 graduate students working in the area (mostly MS candidates).

TECHNICAL COMMENTS ON FERROELECTRIC LIQUID CRYSTALS

Ferroelectric liquid crystals are relatively fast. The time constant is about 50 μ s at <10V and hopefully will be under 10 μ s in the near future. They are not very stable, but the antiferroelectric materials are more stable. Ferroelectric materials normally have memory but do not have gray scale. He felt that gray scale might be possible if the memory property was not used. Ferroelectric materials can be obtained from Chiso and Merck. Fujitsu is also working on ferroelectric liquid crystals. Dr. Uchida felt that optical processing was a good application for these materials.

With respect to TN liquid crystals he commented that the response time between full on or full off or vice versa is much faster than the response time to switch between two midgray levels.

In his opinion, many people like PDLC for projectors because it does not require polarization and therefore can provide more light output. However, one must compromise between light output and contrast. High contrast and high brightness cannot be obtained at the same time. Hysteresis and lag are problems for displaying moving images. Asahi Glass and Dai Nippon Dye are working on displays using PDLC.

With respect to STN, Dr. Uchida felt that very sharp transfer characteristics are needed to get over 400-line resolution at high contrast. This makes it difficult to get good uniformity for color displays. He felt that STN is somewhat limited because the driver cost is as much as the panel cost. The response time of STN is slower than TN, but the response time, viewing angle, and contrast are about the same.

Dr. Uchida has worked on ECB (CSH) displays with Stanley. These displays have good gray scale but are brightness-limited, since they are only good up to about 50% modulation. Their response time is about three times slower than is needed for television display. The viewing angle is very good.

In his work on reflective color displays, Dr. Uchida has achieved a reflectivity of about 20% and a contrast ratio of 5:1. These devices can have a good viewing angle if the scattering angle from the reflecting layer is controlled. These devices use dichroic dyes.

DR. UCHIDA'S GENERAL COMMENTS

The most critical techniques in making LC displays involve the processing of the alignment layer. Surface studies are considered very important. The degree of alignment is controlled by the rubbing time, speed, and pressure.

In producing LC displays a mask must be used over the fringing field area.

The most difficult part of making a retardation film is the adhesive that bonds it to the polarizer. They are sold bonded together.

As a general rule, universities are doing basic research. Devices and materials are developed by companies. Materials are being developed primarily by Chiso, Dai Nippon Dye, and Merck. Dyes are being developed by three or four companies.

For very large direct-view panels, such as will be needed for HDTV, he felt that it will be very costly to make them of AMLCD panels. He felt that PDP would be less expensive since it could be made using a printing process. PDP panels get about one lumen per watt optical efficiency, about the same as AMLCD panels. The AC surface discharge technique has a long life since the phosphor does not have ion bombardment. The discharge electrodes are on one plate and the phosphor is on the opposite plate.

APPENDIX C. GLOSSARY

a-Si- amorphous silicon

a-Si TFT- amorphous silicon thin-film transistor

AGV- automated guided vehicle

ALCOM- advanced liquid crystalline optical materials

AM- active matrix

AMLCD- active matrix liquid crystal display

Anisotropy- directionally dependent

APCVD- atmospheric pressure chemical vapor deposition

Birefringence- having an index of refraction that is different for different polarization of light

Bistable- stable in two conditions

CCD- charge coupled device

CDT- color display tubes

CF- color filters

Chiral- material with either a left or right handed helical arrangement.

CMOS- complementary metal oxide semiconductor

CPT- color picture tubes

CRT- cathode-ray tube

DBS- direct broadcast satellite

DI- deionized

DTI- Display Technologies Inc. (joint venture company by Toshiba and IBM)

ECB- electrically controlled birefringence

EDTV- extended definition television

EL- electroluminescence

Electrodeposition- deposited electrically

ES- engineering services

Ferroelectric- material possessing spontaneous electric polarization

FID- field induction drain

FLC- ferroelectric chiral smectic

FLCD- ferroelectric LCDs

FPDs- flat-panel displays

FPS- frames per second

fps- fields per second

GTC- Giant Technology Corporation

HDTEC- High Definition Television Engineering Corporation

HDTV- high definition television

Homeotropic- liquid crystal uniformity aligned in a direction perpendicular to the planar substrate

HT- high tilt

ISDB- integrated services digital broadcasting

JKTC- Japan Key Technology Center

JSPS- Japan Society for the Promotion of Science

LC- liquid crystal

LCD- liquid crystal displays

LCM- liquid crystal modules

LDD- lightly doped drain

Lenticles- an array of small lenses

Liquid Crystals- states of matter in which the molecules are orientationally ordered but incompletely spatially ordered

LPCVD- low pressure chemical vapor deposition

LSI- large-scale integration

MBBA-(4-n-methoxybenzylidene-4'n-butylaniline)

Microlens- very small lenses

MIM- metal-insulator-metal

MITI- Ministry of International Trade and Industry

MOE- Ministry of Education, Science, and Culture

Monotropic- a liquid crystalline phase which is observed only upon cooling the sample

MOS- metal-oxide semiconductor

MPT- Ministry of Posts and Telecommunications

Multiplexing- switching between two or more locations

NCAP- name given to liquid crystal/polymer dispersions manufactured by the Raychem Corporation

NCIPT- National Center for Integrated Photonic Technology

Nematic- liquid crystalline phase with no spatial ordering of the molecules

NTT- Nippon Telephone and Telegraph

OIS- optical imaging systems

PCM- pulse code modulation

PDLC- polymer-dispersed liquid crystals

PDP- plasma display panels

PECVD- plasma enhanced chemical vapor deposition

Photolithography- use of optically-exposed photoresist masks to produce patterns

Photopolymerization- light induced polymerization

PLC- polymer liquid crystals

p-Si- polycrystalline silicon

RGBG- red, green, blue, green pixel pattern

RGBW- red, green blue & white pixel pattern

RODIC- the name of a Japanese company formed as a joint venture between
Dainippon Ink and Hoffmann LaRoche

SEM- scanning electron microscope

SEMI- Semiconductor Equipment and Materials Institute

SFT- superthin film transistor

Smectic- a liquid crystalline phase where the molecules are arranged in layers

STN- supertwisted nematic

TFEL- thin film electro-luminescent displays

TFT- thin-film transistor

TN- twisted nematic

TPM- total productive maintenance

VGA- video graphic adapters

VLSI- very large scale integration

VTR- video tape recorder

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